Experimental characterization of a fast, pixelated CMOS sensor and design of a Recoil-Proton Telescope for neutron spectrometry

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Abstract

Neutrons are particles of interest in various domains such as fundamental physics, biology, elemental analysis or radio-protection. The measurement of the neutron energy is necessary in all these domains, but the required characteristics of the spectrometers can vary greatly from an application to another. The IPHC laboratory is currently developing a new CMOS pixel Recoil Protons Telescope (RPT). This compact detector allows a real-time reconstruction of the neutron spectrum up to very high flux. The pixelated ultra-fast CMOS sensors were characterized in two proton beam experiments. This experimental characterization was then used in a realistic Monte Carlo simulation of the full system to compute the expected performances. The simulated results exhibit very good spectrometric performances, with an energy resolution better than 4% over a [4.5, 20] MeV energy range. These performances, combined with its compactness and ability to reconstruct the spectrum in real time, make it a very interesting device for various applications.

Keywords: Spectrometry, neutrons, instrumentation, CMOS sensors

1. Introduction

Neutron spectrometry is of primary importance in many fields, starting from nuclear physics, such as fusion plasma experiments [1], nuclear reactor monitor-

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ing [2] and Special Nuclear Materials (SNM) control [3], to medical science with
 an increasing concern about secondary neutron dose in radio- [4] and hadron-
 therapy [5]. Various techniques are currently used to measure neutron energy.
 Time Of Flight (TOF) measurement [6] allows determining neutron spectrum
 with high rate and good resolution but requires a pulsed neutron source and
 a large distance between the source and the detector for high energy neutrons.
 Neutron moderation systems, such as Bonner Spheres Spectrometers (BSS) [7],
 allow measuring neutron spectrum over a large energy range with high preci-
 sion. Although BSS is generally cumbersome, several compact prototypes have
 been developed recently [8] [9]. However, the reconstruction of the neutron
 spectrum still cannot be performed on-line because of the complexity of the de-
 convolution procedure. Neutrons capture allows measuring neutron over a large
 energy range with compact devices [10] but is limited to low-rate measurement.
 While limiting the energy range, recoil proton techniques allow the conception
 of compact real-time high-rate high-resolution neutron spectrometers useful for
 various applications. Various detection systems can be built based on recoil
 protons. A first class of such systems are Time Projection Chamber (TPC).
 TPC are devices that measure the recoil proton trajectory by reconstructing
 its ionization trace inside the volume of the chamber. The electrons created
 inside the chamber are transported by an intense electric field to a discretized
 electrode allowing to reconstruct a 3D trajectory of the recoil proton. The mea-
 surement of the proton energy requiring it to be stopped in the chamber, they
 cannot provide a good resolution for high energy neutrons. We can for example
 cite the μ -TPC device [11], that will also be used at LMDN, that can achieve
 a 5% resolution only up to 4 MeV or the nTPC project [12] of lesser resolu-
 tion. A second class of recoil protons detectors are E/ Δ E detectors. Using
 an unfolding procedure, the energy deposited by the recoil proton in two con-
 secutive detectors is translated into a neutron energy. However, the unfolding
 procedure tends to worsen the energy resolution. As an example, can be cited
 the diamond spectrometer of INFN [13] which achieve a 700 keV resolution at
 12.7 MeV (5.5%). A third class of recoil proton detectors are magnetic spec-

trometers, where the recoil protons are spatially separated according to their
 energy using an intense magnetic field. The magnetic spectrometer of CIAE
 [14] with a resolution of around 1%, is an example of such detectors. However,
 this kind of detector can't be used in our case because of their size and the
 use of an intense magnetic field. Finally, a fourth class of recoil protons de-
 tectors are Recoil Proton Telescopes (RPT). This class can be sub-divided in
 two, depending on the measurement or not of the emission angle of the recoil
 proton. When the angle is fixed using collimators, the efficiency is drastically
 decreased. To overcome this limitation, the converter must be thickened, which
 decreases the resolution. Examples include the HERPT [15] which achieve a
 1.16 MeV resolution at 14.8 MeV (8%) using a 2 mm thick converter. Opening
 the emission angle allows to increase the efficiency, with the price of having to
 measure the angle. The angle is measured by using pixelated detectors, usually
 silicon detectors or plastic scintillators. However, in the first case, the minimal
 energy measurable is restricted by the material budget of silicon sensors, and in
 the second case, the resolution of the device is limited by the ability to recon-
 struct precisely the emission angle. Examples of such detectors are the INFN
 RPT [16] which, combining plastic scintillators and SSDs, was able to measure
 neutron with a resolution better than 5% only for energies higher than 30 MeV,
 or the PSPRT [17] which achieve a 5.2% resolution at 14.1 MeV with plastic
 scintillators. The Institut Pluridisciplinaire Hubert Curien (IPHC, Strasbourg,
 France) is currently developing a new CMOS pixel Recoil Protons Telescope
 (RPT). The telescope being devoted to the measurement of the fast neutrons'
 spectrum of the AMANDE source, the requested features of the CMOS RPT
 that have been set by the Laboratoire de micro-irradiation, de métrologie et de
 dosimétrie des neutrons (LMDN, Cadarache, France) are the following : neu-
 tron energy between 5 and 20 MeV, compact size, measurable flux higher than
 $6 \times 10^5 \text{ n.cm}^{-2}.\text{s}^{-1}$. This paper is the continuation of a previous work [18] where
 we demonstrated the proof of principle of such a telescope. As the frame rate
 of the CMOS sensors used for this first version was insufficient to fulfill the
 required performances, it was mandatory to design a new specific sensor for the

66 final version of this detector.

67 In the first part of this paper, we recall the characteristics of this sensor
68 and present its experimental characterization, that was performed to gather as
69 precisely as possible the sensor's parameters needed for a realistic simulation of
70 the whole design. The new RPT is currently under construction, and neutron
71 measurements with the complete telescope will be presented later in a separate
72 paper. The second part of this paper presents the expected performances
73 provided by the realistic Monte Carlo simulation of the full system.

74 2. Materials and Methods

75 2.1. Neutron spectrometry with a Recoil Proton Telescope

76 To measure the energy of fast neutrons, one can use the elastic diffusion of
77 neutrons which preserves the information of the energy of the neutron while
78 creating a charged particle that can be detected. Elastic scattering can occur
79 on many elements, but highly-hydrogenated materials are generally preferred
80 because of the elastic cross-section around 1 b at 10 MeV and the straightforward
81 reconstruction of the energy thanks to the similarity in mass between proton
82 and neutron.

83 The relation between the energy of the incident neutron E_n , the recoil proton
84 energy E_p , and emission angle θ of the proton is given by:

$$E_n = \frac{E_p}{\cos^2 \theta} \quad (1)$$

85 This means, by measuring the energy and emission angle of the proton, one
86 can directly obtain the energy of the incoming neutron.

87 2.2. Setup

88 The components of the Recoil Proton Telescope developed at the IPHC
89 laboratory are described on Figure 1.

- 90 a) A thin radiator made of polyethylene $((C_2H_4)_n)$ is used to convert the
91 neutrons into detectable protons.

Figure 1: Setup of the Recoil Protons Telescope

- 92 b) The trajectory of the proton is measured by a stack of three CMOS pixel
 93 sensors thinned down to $50\text{ }\mu\text{m}$ thickness to achieve a high-efficiency back-
 94 ground reduction.
- 95 c) To further suppress background, a $65\text{ }\mu\text{m}$ thick veto diode is added right
 96 before the main diode. It allows to veto recoil proton that would be
 97 stopped in the last CMOS sensor or right after, as well as the random
 98 coincidence of such an event with a direct neutron interaction inside the
 99 3 mm thick final diode. It is also used to perform $E - \Delta E$ discrimination,
 100 and therefore reject protons coming from direct neutron interactions in
 101 the diode.
- 102 d) The energy of the proton is reconstructed by a Si(Li) diode of 3 mm thick-
 103 ness, which corresponds to the stopping range of 20 MeV protons.

104 2.3. The FastPixN sensor

105 The CMOS pixel sensor used for the proton track reconstruction, called
 106 FastPixN (Figure 2), has been specially developed for this application. It has
 107 been described in detail in [19]. Its main features are a $15\text{ }\mu\text{m}$ thick fully depleted
 108 high-resistivity epitaxial layer, 128×128 pixels of $50 \times 50\text{ }\mu\text{m}^2$, for a total size of
 109 the sensor of $6.4 \times 6.4\text{ mm}^2$, and 4 bits column-ADC allowing a read-out speed

Figure 2: CAD layout of the FastPixN CMOS sensor

110 of $12\text{ }\mu\text{s}/\text{frame}$, giving a maximal proton flux of $8 \times 10^5\text{ p.cm}^{-2}.\text{s}^{-1}$. Considering
 111 the efficiency presented further in this paper, this proton flux would translate
 112 into a maximal neutron flux of $10^9\text{ n.cm}^{-2}.\text{s}^{-1}$ in the absence of the heavy
 113 background generated by such a high flux.

114 **3. Experimental characterization of the FastPixN sensor**

115 To test the response of the CMOS sensor to protons and evaluate the ac-
 116 curacy of the data reconstruction algorithm, two experiments were performed
 117 at the AIFIRA facility (CENBG-Bordeaux France) and Cyrcé facility (IPHC-
 118 Strasbourg France).

119 *3.1. Experiment at the AIFIRA facility*

120 The AIFIRA facility (Applications Interdisciplinaires de Faisceaux d'Ions en
 121 Région Aquitaine) of the Centre d'Études Nucléaires de Bordeaux Gradignan
 122 (CENBG) produces light ion beams (H^+ , D^+ , He^+) for chemical analysis, char-
 123 acterization and irradiation of materials at various scales, from a millimeter to

hundreds of nanometers. The 3.5 MV Singletron-type single-stage electrostatic accelerator of AIFIRA can deliver ion beams with an energy comprised between 800 keV and 3.5 MeV. Using slits, collimators and electromagnetic lenses, the AIFIRA facility can achieve a spatial resolution of 150 nm. For micro-beam analysis, a scanning system allows to cartography an area from a few microns to a millimeter, depending on the energy and the ion.

The setup of the experiment is represented in Figure 3. This irradiation was made under a 10^{-6} Pa atmosphere with a 100 nm micro-beam of 100 protons of 3.3 MeV per second. The chip was cooled down to -6°C by liquid cooling to reduce the electronic noise.

By irradiating the FastPixN with a highly asymmetric pattern (map of France of $343\text{ }\mu\text{m}$) (Figure 4), the reconstructed 2D signal distribution proved the lack of deformation of the image provided by the sensor. This confirms the good behavior of the acquisition electronic and the accuracy of the data reconstruction algorithm. It must be mentioned that the shift of the first pattern on the top left-hand corner is due to the scanning limit of the AIFIRA vacuum chamber that is not conceived to irradiate uniformly such big samples.

3.2. Experiment at the Cyrcé facility

The Cyrcé cyclotron of IPHC Strasbourg is a 24 MeV proton accelerator allowing to produce radio-isotopes for diagnostic and medical imaging.

Lowering the proton flux to currents down to the fA level, we could study the uniformity of the sensor by irradiating the whole sensor at once, with various energies and with proton currents as low as 0.6 fA (allowing to detect each proton separately). The sensor was placed right after a collimator to minimize the air thickness. The setup of the experiment can be seen on Figure 5.

The sensor was irradiated in three different configurations of the beam with a unique $\varnothing 11\text{ mm}$ collimation.

1. $20.2 \pm 0.2\text{ MeV}$ protons with 1.5 fA
2. $12.0 \pm 0.4\text{ MeV}$ protons with 1.5 fA

Figure 3: Setup of the experiment at AIFIRA

Figure 4: Irradiation of the FastPixN sensor by maps of France separated by $850 \times 850 \mu\text{m}$. A cut at 150 counts per pixel was applied to suppress background

153 3. $4.0 \pm 0.7 \text{ MeV}$ protons with 0.6 fA

154 The time-consistency of the beam was checked during the measurement and
155 was found to be constant, as well as the spatial uniformity ($\sigma \approx 0.7\%$).

156 On Figure 6 can be seen an example of X-Y counting map for 12 MeV pro-
157 tons. The spatial response of the sensor was found to vary both in counting

Figure 5: Setup of the experiment at the Cyncre facility

Figure 6: Image of the irradiation of the FastPixN with protons of 12 MeV

range and detected charge (ADC value). It is observed that the higher the energy, the higher the variability. Moreover, by projecting first over X/Y then over count/charge, the distribution of the value of count/charge along the X/Y axis is obtained. It is observed that, whereas the overall variability is small in the X direction (columns) ($\sigma \approx 3\%$ for counts and $\sigma < 4\%$ for ADC value for

all energies) (Figure 7), it is much larger in the Y direction (rows) ($\sigma \leq 25\%$ for counts and $\sigma \leq 10\%$ for ADC value for all energies) (Figure 8). Statistical uncertainty is around 2% for each row/column. To compare between measurements of various duration and energy, counts (charge) was normalized by the total counts (charge) of each measurement.

Figure 7: Variability of charge and counting rate along X (columns)

Figure 8: Variability of charge and counting rate along Y (rows)

The significant variation of the response between columns can be explained by the electronics of the sensor. Each column uses its own amplifier whereas 8 columns are read by the same ADC, whose threshold can be tuned. The individual response of the columns cannot be normalized at the electronics level. However, by calibrating each column during the off-line data analysis, the same overall variability than for rows should be reached. This overall variability of 3-4% is good enough for neutron spectrometry as the FastPixN sensors will not

175 be used to directly reconstruct the energy of the proton, but only as a rough
176 cut comparing the energy deposit between consecutive sensors.

177 3.3. Energy calibration

178 An energy calibration was performed at the Cyncé facility with a proton
179 beam of constant energy and a set of attenuators of calibrated thicknesses,
180 resulting in protons with energies in the range [4, 24] MeV. The proton energies
181 and corresponding Al attenuator thicknesses can be found in Table 1.

Table 1: Characteristics of the Cyncé modulation wheel

Al (mm)	0	0.147	0.290	0.431	0.568	0.701	0.842	0.990	1.133	1.278
E_p (MeV)	23.71	22.99	22.30	21.6	20.9	20.2	19.5	18.7	17.8	17.0

Al (mm)	1.424	1.564	1.714	1.862	2.007	2.156	2.296	2.448	2.599	2.761
E_p (MeV)	16.1	15.2	14.2	13.1	12.0	10.8	9.6	8.1	6.4	4.0

182 To be able to achieve the calibration, the energy deposited inside the epi-
183 taxial layer must be calculated. This was done by simulating the irradiation
184 experiment with Geant4 version 10.01.p01 [20]. The energy deposited inside
185 the epitaxial layer of the CMOS sensor was calculated using Monte Carlo sim-
186 ulations. The sensor was modeled in detail as described in section 4.1. For the
187 cyclotron, the elements that were reconstructed in the simulation were the last
188 stage of the vacuum tube, the corresponding energy degrader for each energy
189 (without the full wheel), the collimator and the sensor.

190 The combination of the measurement at Cyncé and the Geant4 simulation
191 output allowed to construct an energy calibration curve (Figure 9), and to esti-
192 mate an energy resolution of around 35 keV/ADC.

193 As designed, the FastPixN is capable of properly measuring protons up to
194 20 MeV, corresponding to a deposited energy of 47 keV. Figure 9 shows a lin-
195 ear relation between ADC signal and deposited energy in the range [0.055, 0.18]

Figure 9: Calibration curve of the whole FastPixN

MeV, corresponding to protons in the range [4, 17] MeV. At lower deposited energy (higher proton energy), non-linear effects appear due to the charge collection inefficiency. The calibration curve demonstrates the good behavior of the sensor, but it must be stressed that the CMOS pixel sensors are mainly for tracking purpose and that a precise calibration is therefore not a prerequisite for the spectrometric performances. However, the energy information will be used to discriminate against various backgrounds.

To reduce the dispersion of the spatial response (see section 3.2), a calibration for $E_{dep} > 60$ keV was also made independently for each column of the sensor. Figure 10 shows the slope of each calibration curve as a function of the column position (Y). The variability ($\approx 16\%$) of the slopes confirms the need to make a column-by-column calibration of the sensors.

It can also be noticed that the simulation of the energy deposition in the FastPixN allowed to assess that the oxide layer is not 6 μm thick as claimed by the manufacturer but in fact 8 μm . This correction is important because it will also change the total energy deposited in a RPT containing 3 FastPixN sensors, and thus the minimal energy that can be measured by such a device.

Figure 10: Calibration curve slope for each FastPixN column for $E_{dep} > 55$ keV. The study was restricted to the center of the Cýrcé beam

214 The experimental characterization of the sensor with two different proton
 215 beam experiments has allowed both to validate the data reconstruction algo-
 216 rithm, and to determine the spatial and energetic dispersion of the pixel re-
 217 sponses. With a column-by-column calibration, a 4% dispersion can be achieved
 218 on the full sensor (128×128 pixels). This 4% dispersion is nevertheless negli-
 219 ble compared to the estimated energy resolution of the sensor (35 keV/ADC for
 220 energy deposits between 45 and 180 keV, corresponding to a resolution of 20 to
 221 75%), and the global sensor performances are found compatible with a tracking
 222 purpose. This experimental characterization was used as a realistic input for
 223 the simulation of the whole RPT. The energy resolution and spatial dispersion
 224 have been considered to determine as precisely as possible by simulation the
 225 expected performances of the RPT for neutron spectrometry.

226 4. Neutron spectrometry

227 4.1. Monte Carlo simulation of the RPT

228 The Recoil Protons Telescope is under development at the IPHC labora-
 229 tory. To optimize the geometry of the detector and estimate its performances,

a full simulation of the RPT with Geant4 software (version 10.01.p01) using the physics list QGSP_BERT_HP, was carried out. The RPT was modeled as follows.

- The radiator was modeled as a cylinder of homogeneous polyethylene of 4.5 mm radius and variable thickness.
- The CMOS sensor was modeled as an oxide layer of pure SiO_2 with 8 μm thickness, an epitaxial layer of 10^{13} cm^{-3} p-doped Si with 10 μm thickness and a bulk of 10^{17} cm^{-3} p-doped Si with 34 μm thickness. An ideal charge collection in the epitaxial layer was considered, which was proved experimentally up to 20 MeV protons. The energetic and spatial resolution of the sensor were implemented by rounding the value to 35 keV and 15 μm respectively (see section 3.3).
- The veto diode was modeled as a 65 μm thick, 4.5 mm radius cylinder of pure Si.
- The diode was represented as a 3 mm thick, 4.5 mm radius cylinder of pure Si. The experimental energy resolution of the diode was implemented.

To evaluate the expected performances of the RPT for neutron spectrometry, mono-energetic spectra of 5, 7, 10 and 14 MeV and the reference ISO AmBe spectrum [21] have been considered in the simulation.

4.2. Proton energy resolution

The first step of the optimization of the RPT parameters was the quantification of the effect of the uncertainty sources on the reconstruction of the proton energy. This study allows to later choose which parameters are critical to improve the energy resolution of the spectrometer.

The proton energy is reconstructed by summing the energy deposited in the diodes and the estimated energy lost in the rest of the RPT. This energy loss has been estimated using Monte Carlo simulations for each material constitutive of the RPT (converter, CMOS sensors, air gaps, etc.). To reconstruct

the proton initial energy, the mean value of the obtained distributions is used. The added energies for normal protons can be seen on Figure 11 (left). An estimate of the error on the reconstructed energy is provided by the dispersion of this distribution (Figure 11 (right)). However, besides energetic straggling,

Figure 11: Monte Carlo estimate of the energy loss of normal protons passing through various elements of the RPT as a function of the energy deposit in the diodes (left). Monte Carlo estimate of the initial energy of a normal proton and reconstruction error, as a function of the energy deposit in the diodes (right)

one has also to consider angular straggling. To estimate the contribution of both factors, a simulation of an ideal RPT was performed. The n-p conversion rate being of some 10^{-3} per mm of polyethylene, this small number puts some constraints on the simulation procedure. To save time and memory resources without impacting statistics, we decided to simulate directly a fictive proton source located inside the converter. Protons were therefore created randomly inside it within a 45° aperture cone, to obtain a full irradiation of the first FastPixN sensor. For a $50\text{ }\mu\text{m}$ converter and 10 MeV protons the minimal total uncertainty on the proton energy was found to be $\sigma_{\text{tot}} = (0.86 \pm 0.01)\%$. The main uncertainty source is the inability to know the exact position of creation of the proton inside the monolithic polyethylene radiator, preventing a good estimation of the proton energy lost inside it. This effect corresponds to creating an uncertainty of $\sigma_{\text{conv}} = (0.71 \pm 0.01)\%$. However, with such a thin converter, the impact of angular straggling on the determination of the emission angle re-

276 mains small with an uncertainty on the cosine of $(0.30 \pm 0.01)\%$. The energetic
 277 straggling inside the FastPixNs and in the air gaps contribute respectively to
 278 $\sigma_{\text{CMOS}} = (0.50 \pm 0.01)\%$ and $\sigma_{\text{air}} = (0.13 \pm 0.01)\%$. The quadratic sum of the
 279 uncertainties on the energy $((0.88 \pm 0.01)\%)$ is compatible with a lack of other
 280 uncertainty sources. Adding the experimentally-measured energy resolution of
 281 the diode ($\approx 1.04\%$ at 10 MeV), the minimal uncertainty on the reconstructed
 282 neutron energy derived from the Monte Carlo simulation for 10 MeV protons
 283 was $\overline{\sigma}_n = (1.4 \pm 0.7)\%$, which is a very good achievement compared to standard
 284 metrological requirements (5%). However, various other effects such as the pres-
 285 ence of background events need to be considered to compute a precise neutron
 286 energy resolution of the RPT system. A full simulation was therefore performed
 287 considering a point-like neutron source at 75 cm irradiating in a cone comprising
 288 the full detector. The result of this simulation is presented thereafter.

289 In the following sections, background is defined as an event producing a
 290 hit in each CMOS sensors and in the diode without coming only from a recoil
 291 proton produced in the converter. It therefore comprises random coincidences
 292 of events, recoil protons or not, as well as true coincidences of particles other
 293 than recoil protons produced in the converter, and particles produced outside
 294 of the converter.

295 *4.3. Expected neutron spectrometry performances*

296 Using a Monte Carlo Geant4 simulation based on the experimental char-
 297 acterization of the CMOS sensors and the optimization of reconstruction cuts
 298 in the simulation, the expected performances of a RPT equipped with Fast-
 299 PixN pixel sensors can be computed for mono-energetic and continuous neutron
 300 spectra.

301 For mono-energetic neutrons of 5, 7, 10 and 14 MeV, the best resolution
 302 would be achieved with a $50\text{ }\mu\text{m}$ thick converter (Figure 12). The expected
 303 performances are summarized in Table 2. A loss of resolution beginning at
 304 10 MeV, due to the increasing inelastic cross-section and the decreasing elastic
 305 one, is observed. This leads to an increased quantity of events with an ap-

parent high negative $\Delta E/E$, corresponding to neutrons reconstructed with an energy far below their true one (low energy inelastic protons considered as elastic protons). There is therefore a decreasing signal-over-noise ratio, leading to a worsening of the resolution.

Figure 12: Reconstruction of 5, 7, 10 and 14 MeV neutron peaks (blue) from a Geant4 simulation of FastPixN RPT. Peaks are fitted with a Gaussian function (red)

309

Table 2: Results for mono-energetic peaks with a 50 μm converter

Energy	Efficiency	Mean energy (MeV)	Fitted resolution
5 MeV	$(1.74 \pm 0.05) \times 10^{-5}$	4.931 ± 0.005	$(3.29 \pm 0.06)\%$
7 MeV	$(1.83 \pm 0.05) \times 10^{-5}$	6.990 ± 0.005	$(1.98 \pm 0.05)\%$
10 MeV	$(1.59 \pm 0.05) \times 10^{-5}$	9.990 ± 0.006	$(1.27 \pm 0.05)\%$
14 MeV	$(1.45 \pm 0.05) \times 10^{-5}$	14.041 ± 0.009	$(1.10 \pm 0.06)\%$

For the reconstruction of an AmBe spectrum ($[0, 11]$ MeV), the best resolution would be also achieved with a 50 μm thick converter. The obtained average energy resolution was $(3.54 \pm 0.07)\%$, with an average efficiency of $(1.44 \pm 0.03) \times 10^{-5}$ over a $[4.5, 11]$ MeV neutron energy range. The background level was found to be only $(0.9 \pm 0.2)\%$.

Figure 13: Simulated RPT raw output with a 50 μm thick converter

Thanks to its ultra-fast FastPixN CMOS sensors, the RPT is barely affected by high flux of neutrons. From simulation, no loss in performances was found for a flux of $2.5 \times 10^6 \text{ n.cm}^{-2}.\text{s}^{-1}$, and a loss of only 1% of resolution was found for a flux of $4 \times 10^7 \text{ n.cm}^{-2}.\text{s}^{-1}$ (from $(3.54 \pm 0.07)\%$ to $(4.52 \pm 0.07)\%$), with a final background level of only $(2.3 \pm 0.3)\%$ despite a fortuitous coincidence rate of $(33.6 \pm 0.07)\%$.

5. Conclusion and Prospective

An evaluation of the expected performances of a new CMOS-pixel-based Recoil Proton Telescope neutron spectrometer was performed using a realistic simulation based on the experimental characterization of the sensors. For mono-energetic neutrons from 5 to 14 MeV and an AmBe spectrum, the energy resolution was found to be better than 4%. Thanks to its CMOS sensors, this device should be able to perform measurement up to a neutron flux of $10^9 \text{ n.cm}^{-2}.\text{s}^{-1}$ in the range $[4.5, 20] \text{ MeV}$. Its performances, compactness and ability to reconstruct the spectrum in real time make it a very interesting device for various applications comprising the measurement of secondary neutrons in protontherapy [5] or the identification of SNM through their neutron signature [3].

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