Performance of the high-efficiency thermal neutron BAND-GEM detector

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1. Introduction

Neutron diffraction and spectroscopy experiments using thermal neutrons are the core activity at spallation neutron sources. Detection systems nowadays make great use of $^3$He-based gaseous detectors that offer the possibility to cover large areas ($\text{m}^2$) and have an intrinsic efficiency to thermal neutrons higher than 80%. The $^3$He shortage [1] and its massive use in applications linked to homeland security have determined an exponential rise in its price, preventing its use for research applications including future neutron sources such as the European Spallation Source (ESS [2]). In the case of ESS, together with the need for replacing $^3$He, it is essential to develop high-rate neutron detectors [3] able to fully exploit the increased neutron flux of ESS relative to the present neutron sources.
sources [4]. The situation calls for the development of large-area and high-rate neutron detectors that do not use $^3$He but have a comparable detection efficiency with a price ideally not exceeding 500 k€/m$^2$ and a spatial resolution between 1–10 mm. This paper describes a new detector based on the Gas Electron Multiplier (GEM) technology [5–8] that is able to detect beams at high rate (>1 MHz/mm$^2$) and gives the possibility of covering large areas at low cost. Although GEM-based detectors are mostly used to detect charged particles, they can be adapted (typically by using a customized cathode configuration) to detect neutral particles, such as neutrons and photons [9–12]. Several GEM detectors for fast and thermal neutron detection have been realized during recent years [13–30].

The BAND-GEM detector described in this paper aims at increasing the thermal neutron detection efficiency with respect to single-layer boron-based detectors such as the one described in Ref. [19] since its design has been optimized for cold neutron energies. The strategy that has been adopted consists in the realization of a cathode with 3D structure similarly to that which is described in Refs. [31–33].

2. BAND-GEM detector construction

2.1. Principle of operation

The boron array neutron detector based on the GEM technology (BAND-GEM) described in this paper is constituted by a triple GEM detector equipped with a 3D converter cathode. The detector has an active area of $5 \times 10$ cm$^2$. Fig. 1 shows a scheme of the detector layout. The first element at the bottom is a thin aluminum cathode. The 3D converter is made of a stack of 24 aluminum grids coated with about 0.59 μm of $^{10}$B$_4$C (99% purity; see Fig. 2). Each grid is 3 mm high, has an overall area of $12 \times 7$ cm$^2$, and is composed of 11 strips 10 cm long, 3 mm high, and 200 μm thick. The pitch between the strips is 4 mm. All around the strips, there is an external frame that is 1 cm thick and that also becomes borated during the deposition. The internal side of this thick frame represents the boundary of the detector active area. Between the grids, there are 1 mm thick spacers made from fiberglass. Three standard GEM foils and an anode with pads of different dimensions are placed on top of the borated grid stack. If the full detector is inclined by few degrees (less than 10°) with respect to the incoming beam, neutrons are forced to cross the boron layers at grazing angles.

![Fig. 1. Detector schematics and principle of operation.](https://academic.oup.com/ptep/article-abstract/2018/2/023H01/4913660)
Fig. 2. Example of the 3 mm thick grids used in the converter after $^{10}\text{B}_4\text{C}$ coating. The thickness of the thin walls is 200 μm. The external area of the grid is $12 \text{ cm} \times 7 \text{ cm}$; the frame surrounding the thin walls is 1 cm thick.

As a consequence, the interaction probability, as well as the detection efficiency, is augmented while keeping the beam perturbation small (due to the reduced volume of non-active material). Moreover, conservation of energy and momentum for the $n(^{10}\text{B}, ^7\text{Li})\alpha$ occurring in the layer implies that the two charged particles ($^7\text{Li}$ and $\alpha$) are emitted back to back with kinetic energies in the order of 1 MeV. This means that at least one of the (charged) reaction products is likely to leave the $^{10}\text{B}_4\text{C}$ layer and thus be revealed. The gas mixture used in the detector is Ar/CO$_2$ 70%/30% and it is characterized by a mean work function of approximately 27 eV [34]. In order to get a signal, the primary electrons created either by alpha particles or $^7\text{Li}$ ions must be able to move inside the grid system and reach the triple GEM structure where they are multiplied.

2.2. The grid system engineering

In order to extract the primary charge, each grid is kept at a different voltage: this allows generation of a drift field in the system that is as uniform as possible. A particular $^{10}\text{B}_4\text{C}$ coating procedure [35–37], performed at the ESS thin film deposition facility in Linkoping, co-located with Linkoping University [38], was studied in order to coat the thin walls of the grids that represent the active conversion area. The grid system can thus be considered as a field cage (similarly to what is done in Ref. [39]) and the potential to each grid is given through an external voltage divider that has the two ends connected between the planar cathode and the grid closest to the triple GEM.

A detailed engineering design (see Fig. 3, top-left) has been performed in order to realize the full system, guaranteeing that each grid is correctly positioned, sustained, and gets the right potential. The critical parameters for optimization of the detector performances are described in Table 1.

Due to the complexity of the problem, numerical simulations using IDL [40] and Ansys+Garfield software [41,42] have been performed for the optimization of these parameters. These simulations are described in another paper [43].

2.3. Detector assembly and signal read-out

Fig. 3 and Fig. 4 show a series of pictures of the detector assembly and containment box. The triple GEM box is closed on top of the grid box and the appropriate electric contacts are realized. This BAND-GEM detector is equipped with a padded anode (see Fig. 4, right panel) composed of 128 pads, each with different dimensions ($4 \text{ mm} \times 3 \text{ mm}, 4 \text{ mm} \times 6 \text{ mm}, 4 \text{ mm} \times 12 \text{ mm}$). The pads were realized with a step of 4 mm in the $x$-direction in order to match the strip pitch. The gap between two adjacent pads is equal to 200 μm, corresponding to the thickness of the thin strips. One of the
Fig. 3. 3D converter system: (a) Exploded view of the detector CAD design describing the different components of the device, (b) 3D converter system completely assembled, (c) 3D converter system after its final insertion in the detector gas box. The white screws used for fixing are also used for alignment. The coordinate axes are described in Fig. 6 relative to the pad position. The $z$-axis represents the neutron direction when the detector is used at grazing angles.

Fig. 4. Final detector assembly: view from the lateral diagnostic window of the 3D converter (a); mounting of the triple GEM on top of the 3D converter (b); photo of the anodic pads read-out (c).

Table 1. Geometrical and electrical parameters of the present detector.

| Geometrical parameter                  | Value                      |
|----------------------------------------|----------------------------|
| Strip pitch                            | 4 mm                       |
| Grid thickness                         | 3 mm                       |
| Spacer thickness                       | 1 mm                       |
| Number of walls per grid               | 11                         |
| 3D converter dimensions                | 10 cm ($x$) · 5 cm ($y$) · 9.6 cm ($z$) |
| Strip thickness                        | 200 μm                     |
| Grid bulk material                     | Aluminum Al5754            |
| $B_4C$ resistivity                     | 696 Ω cm                   |
| $B_4C$ thickness on Al strips          | 0.55 μm                    |
| Divider resistors                      | 24 of 8 MΩ                 |
| Maximum resistor current               | 100 μA                     |
| Maximum applied voltage (bottom grid of the stack) | 14.9 kV                  |
| Minimum applied voltage (top grid of the stack) | 3.3 kV                   |

The most important procedures that was performed is the alignment of the pads with the 3D converter system. The alignment was obtained by means of centering holes positioned both in the detector box and in the detector lid where the anodic pads are located. By referring to this mechanical reference, an alignment better than the centering hole tolerance (about 1/10 mm) was obtained.
3. Performance measurement using neutrons

3.1. Experimental setup at the EMMA beamline at ISIS

The detector was tested for the first time with a neutron beam on the EMMA instrument at Target Station 1 at ISIS. Instruments located at Target Station 1 receive 4 pulses out of 5 coming from the source operating at a frequency of 50 Hz. The aim of the experiment was to conduct a characterization of the detector, and measure the efficiency of the detector with respect to the tilt angle and the neutron wavelength. EMMA is a new instrument at ISIS. It is located at the place of the previous HET instrument [48]. The EMMA beam has maximum dimensions of 45 × 45 mm² but motorized jaws can define smaller beam sizes. The nominal beam divergence is a few mrad. The sample position is 16 m from the moderator and is provided with a rotating and movable support. The range of available neutron wavelengths is approximately \( \lambda = 1 - 4 \times 10^{-10} \) m corresponding to the energy range \( E_n = 5 - 81 \) meV. The incident beam monitor, positioned immediately behind the jaws (i.e., the beam dimension selector), is a commercial GS-20 lithium glass scintillator with an efficiency at \( \lambda = 1 \AA, \varepsilon_{\text{bm}} = 1 \times 10^{-10} \) m) = 0.60% ± 0.06%. The beam monitor efficiency scales linearly with \( \lambda \) in the range of interest of the instrument. A scheme of the EMMA setup is shown in Fig. 5 and the pad layout is shown in Fig. 6. The \( \theta \) angle is defined as the BAND-GEM tilting angle with respect to the incoming neutron beam and it is shown in Fig. 1. \( \theta \) is set using a turntable with a precision better than 0.1°.

Different setups were used for the various measurements performed, as summarized in Table 2. The BAND-GEM detector was positioned in the beam immediately behind the beam monitor and it was mounted on the \( x/y/z/\theta \) positioner. In Fig. 7 the setups for \( \theta = 0^\circ \), with the cathode facing the beam source and \( \theta = 90^\circ \) where the beam hits the side of the 3D converter passing through a diagnostic window, are shown.

The voltage divider of the 3D converter was biased using two channels of the 15 kV high-voltage module, while the triple GEM was biased using the custom-made HVGEM module. Following
Table 2. List of the measurements performed on the EMMA beamline. The definition of the coordinates $x, y,$ and $z$ is shown in Fig. 3(c), where two diagnostic windows are also visible on the cathode plane ($x - y$) and along the 3D converter. $\theta$ is the tilt angle of the movable support. The potential differences $V_1$, $V_2$, and $V_3$ are defined later in Fig. 9.

| Experimental setup used | Measurement performed |
|------------------------|-----------------------|
| $\theta = 0^\circ$     | $V_1$, $V_2$, $V_3$ scans (see text for details) |
| $\theta = 90^\circ$    | $Z$ scan (extraction efficiency $\eta_C$) |
| $0^\circ < \theta < 6^\circ$ | Efficiency $\varepsilon$ |
| $0^\circ < \theta < 5^\circ$ | Position resolution (FWHM) |
| $\theta = 5^\circ$, $1 \cdot 10^{-10}$ m $< \lambda < 4 \cdot 10^{-10}$ m | Efficiency $\varepsilon$ |

In this configuration, the maximum achievable value of electric field inside the grid system is about 1.5 kV/cm. The gas used during all the measurements is a 70%/30% Ar/CO$_2$ mixture with a flow rate of about 20 l/h. Since the detector volume is 4.4 l, this means that during a 24 h period, the gas was replaced about 100 times.

3.2. Time of flight analysis

Due to the pulsed structure of the ISIS spallation source, energy-resolved measurements can be performed using the time of flight technique (ToF). This feature represents a crucial point in the characterization of the response of the BAND-GEM at different neutron wavelengths. The LVDS signals generated by the CARIOCAs were routed to a user-designed FPGA board that formed the interface between the front-end electronics and the standard ISIS data acquisition electronics (DAE), known as DAE2 [50]. Data from the CARIOCAs were first buffered inside the FPGA, using an individual buffer per GEM pad, so that the interface electronics did not introduce any additional dead time. When the FPGA found data in one of the buffers, the position of the corresponding GEM pad that generated the signal was sent to the DAE for histogramming. The DAE performed the time
Fig. 7. BAND-GEM setup on EMMA for $\theta = 0^\circ$ (left) and $\theta = 90^\circ$ (right).

Fig. 8. Time of flight spectra recorded for one of the BAND-GEM pads (top) and for the EMMA GS20 beam monitor (bottom). The neutron exposure time was 6 hours and 30 minutes, corresponding to a proton current of 950 $\mu$A.

Stamping of these events and incremented the corresponding bin in the ToF histogram associated with this GEM pad, thereby creating a ToF spectrum $S_i(t)$ for each BAND-GEM pad. The bin width applied by DAE for ToF spectra reconstruction is 100 $\mu$s. Given that neutrons can travel up to about 96 mm in the 3D converter system, it is important to verify that the time spent by the neutron before being captured has a negligible effect on the ToF measurement. An error on the ToF measurement induces a wrong reconstruction of the neutron wavelength. Once captured, the delay introduced by the drift of the primary electrons (coming from charged neutron product ionization) in the 3D converter system can be considered negligible since the average electron velocity inside the 3D converter system is about 7 cm/$\mu$s [49], which is much higher than the velocity of incoming neutrons. The range of neutron velocity on EMMA is approximately between $v_1 = 3950$ m/s ($\lambda = 1 \cdot 10^{-10}$ m) and $v_2 = 990$ m/s ($\lambda = 4 \cdot 10^{-10}$ m). Neutrons with such velocities can introduce a delay up to 25 $\mu$s and 100 $\mu$s, respectively. Since this delay is comparable with the bin width used by the DAE, it may introduce a maximum absolute error on neutron wavelength determination that is less than $0.025 \cdot 10^{-10}$ m. The signal from the reference EMMA beam monitor was also routed to the DAE2 and a time of flight spectrum $M(t)$ was also created for this detector. The results are shown in Fig. 8. Time of flight spectra obtained with the two detectors (BAND-GEM and beam monitor) are consistent.

The analysis for different neutron wavelengths is performed by slicing the ToF spectrum. The relation between ToF and neutron wavelength for EMMA is shown in Table 3.
Table 3. ToF and $\lambda$ relationship on EMMA.

| $\lambda$ ($10^{-10}$ m) | ToF (ms) |
|--------------------------|----------|
| 1                        | 4.000    |
| 2                        | 8.060    |
| 3                        | 12.560   |
| 4                        | 17.060   |

Fig. 9. Definition of the $V_1$, $V_2$, and $V_3$ parameters: $V_1$ is the potential difference applied across the full 3D converter, $V_2$ is the potential difference between the top grid and the bottom of the first GEM, and $V_3$ is the sum of the three potential differences applied to the triple GEM stage.

The counting rate for a certain $\lambda$ interval is thus calculated for the $i$th pad of the BAND-GEM and for the beam monitor, respectively, as

$$C_i(t = \lambda) = \int_{t_1}^{t_2} S_i(t)dt$$
$$C_M(t = \lambda) = \int_{t_1}^{t_1} M(t)dt,$$

where $t_1$ and $t_2$ represent the ToF interval used for the calculation and $S_i(t)$ and $M(t)$ are the ToF spectra. If more than one BAND-GEM pad is hit by the beam, the quantity

$$I_{\text{GEM}} = \sum_{i=1}^{n} C_i$$

represents the integrated counting rate for that specific $\lambda$ interval over all the $n$ active pads.

3.3. Working point determination

In order to establish the BAND-GEM working point, three potential difference scans have been performed for the three main voltage values (for simplicity named $V_1$, $V_2$, and $V_3$) shown in Fig. 9.

All measurements for the working point determination were performed at $\theta = 5^\circ$ using a neutron beam with dimensions of 4 mm $\times$ 4 mm. The beam footprint reconstructed using this setting is shown in Fig. 10.

3.3.1. $V_1$ scan

The integrated counting rate $I_{\text{GEM}}$ is an increasing function of $V_1$ and in particular it reaches a plateau for values higher than 8 kV (see Fig. 11). The occurrence of a plateau indicates that the
Fig. 10. Beam footprint reconstructed using a beam dimension of $4 \text{ mm} \times 4 \text{ mm}$ and a tilting angle $\theta = 5^\circ$. The color scale represents $C_i$ (integrated counts) normalized to the pad area calculated for $1 \cdot 10^{-10} \text{ m} < \lambda < 4 \cdot 10^{-10} \text{ m}$. For the coordinate axis definition see Fig. 5(b).

Fig. 11. $V_1$ scan. $I_{\text{GEM}}$ is calculated for $1 \cdot 10^{-10} \text{ m} < \lambda < 4 \cdot 10^{-10} \text{ m}$.

charge extraction efficiency (see Sect. 3.4) is practically saturated. A value of $V_1 = 11.1 \text{ kV}$ was chosen as the working point.

3.3.2. $V_2$ Scan
The integrated counting rate $I_{\text{GEM}}$ is a slowly increasing function of $V_2$ and reaches a plateau for values higher than 1.2 kV. A value of $V_2 = 1.5 \text{ kV}$ was chosen as the working point.

3.3.3. $V_3$ scan
The gas gain of triple GEM-based detectors depends exponentially on $V_3$. Due to the loss of primary charge in the 3D converter (see Sect. 3.4), it is useful to increase the gas gain. However, as already shown in previous papers, too high a gain makes GEM-based detectors sensitive to gamma-ray background [51].

$I_{\text{GEM}}$ for $1 \cdot 10^{-10} \text{ m} < \lambda < 4 \cdot 10^{-10} \text{ m}$ was measured as a function of $V_3$ and the results are shown in Fig. 13. The two curves shown in Fig. 13 represent an open/free beam measurement (circles) and a measurement with a 1 mm thick sheet of Cd interposed between the EMMA jaws and the BAND-GEM (square). The second setup was used to measure the gamma sensitivity of the detector, since the Cd foil stops all thermal neutrons with energies lower than 0.5 eV (i.e., $\lambda > 0.4 \cdot 10^{-10} \text{ m}$).
and through neutron capture generates gamma rays with energy ranging between 0.6 and 4 MeV [52]. The counting rate is an increasing function of $V_3$ and, as expected, the detector starts to detect thermal neutrons at a voltage $V_3 = 810$ V (i.e., a gain of about 50). In order to increase the counting rate, the voltage was set to 1020 V and a slight variation of the slope of the curve is observed at $V_3 = 920$ V. The gain corresponding to this voltage (about 300) was interpreted as the gain where the detector starts to be sensitive to gamma rays. This statement is confirmed by the Cd measurement where $I_{GEM}$ changes slope for $V_3 > 900$ V, which corresponds to an effective gas gain >200. This result is comparable with that obtained previously and described in Ref. [51]: according to the results presented in Ref. [51] the GEM detector has sensitivity to gamma rays of about $10^{-5}$ at this gain. A value of $V_3 = 900$ V was chosen as the working point.

### 3.4. Measurement of charge extraction efficiency $\eta_C$

One of the most important parameters to be determined when working with a 3D converter that also operates as a field cage is the capability of extracting the primary charge that is released by neutron capture products (either alphas or Li ions). In order to perform these measurements, the neutron beam area was set to $4 \text{ mm} \times 4 \text{ mm}$ and $\theta$ was set to 90° so that the beam entered the 3D converter from the side through a diagnostic window that has dimensions of 75 mm $(z) \times 100$ $(x)$ mm (see Fig. 4 and Fig. 7). The beam position was moved along the $z$ axis (see Fig. 3) and the measurement...
Fig. 14. Beam footprint reconstructed using a beam dimension of $4 \text{ mm} \times 4 \text{ mm}$ and a tilting angle $\theta = 90^\circ$. The color scale represents $C_{\text{BAND-GEM-PAD}}$ (integrated counts) normalized to the pad area calculated for $1 \cdot 10^{-10} \text{ m} < \lambda < 4 \cdot 10^{-10} \text{ m}$. The arrow indicates the incident neutron direction. For the coordinate axis definition see Fig. 5(b).

Fig. 15. Measurement of the charge extraction efficiency for different $V_1$. was repeated for different $V_1$ values ranging from 3.3 kV to 11.1 kV. The beam footprint for one of the measurements is shown in Fig. 14.

The results of $z$ scans for different $V_1$ are shown in Fig. 15.

In Fig. 14 the plots of the $z$ scan for six different values of $V_1$ are shown. The width of the lateral diagnostic window is only 75 mm, meaning that the range that can be completely explored is $12 \text{ mm} < z < 68 \text{ mm}$ using a beam of $4 \text{ mm} \times 4 \text{ mm}$: in this range $I_{\text{GEM}}(z)$ is found to be linear for $V_1$ values that are not too low. Outside this $z$ range the values of $I_{\text{GEM}}$ can be extrapolated from the measured ones, as shown in Fig. 14. The relative charge extraction efficiency $\eta_C$ is defined as $\eta_C = I_{\text{GEM}}(z = 0 \text{ mm})/I_{\text{GEM}}(z = 96 \text{ mm})$ and the values for different applied $V_1$ are shown in the different panels of Fig. 14 ($z = 0 \text{ mm}$ at the bottom and $z = 96 \text{ mm}$ is at the top of the 3D converter).
Ideally one would like $\eta_C$ to be as close as possible to unity, which would provide uniform charge extraction efficiency. This is not the case and a fraction of charge is inside the 3D converter. The linear dependence of $I_{\text{GEM}}$ on $z$ suggests that the loss is caused by a geometrical effect (the physical presence of grids). The last panel of the figure, however, shows that at too-low voltages the charge extraction is not satisfactory.

### 3.5. Neutron detection efficiency determination

The neutron detection efficiency was measured using a beam dimension of $4 \text{ mm} \times 4 \text{ mm}$ and for $\theta$ values ranging from $0^\circ$ to $6^\circ$. In this configuration the beam footprint is similar to the one shown in Fig. 10. The efficiency $\epsilon_{\text{GEM}}$ of the BAND-GEM detector was obtained as:

$$
\epsilon_{\text{GEM}}(\lambda) = \frac{I_{\text{GEM}}(t = \lambda)}{C_M(t = \lambda)} \times \epsilon_1,
$$

where $\epsilon_1 = \epsilon_{\text{bm}} (\lambda = 1 \cdot 10^{-10} \text{ m}) = 0.60\% \pm 0.06\%$. The efficiency of the beam monitor has previously been measured using a well calibrated $^3\text{He}$ detector as reference. The working point values $V_1 = 11.1 \text{ kV}$, $V_2 = 1.5 \text{ kV}$, $V_3 = 0.9 \text{ kV}$ obtained in the previous section have been used in the following measurements.

#### 3.5.1. Efficiency measurement as a function of tilting angle $\theta$

The detector efficiency was determined as a function of $\theta$ for two wavelengths by considering the corresponding ToF periods. Fig. 16 shows that for $\theta > 2^\circ$ the detector reaches an efficiency plateau of about 17% and 30% for $\lambda = 1$ and $2 \cdot 10^{-10} \text{ m}$, respectively. The measurement is compared to a numerical simulation (using IDL, Ansys, and Garfield++) that has been superimposed. Fig. 16 shows that the measurement and simulation results are comparable. The small dips that can be observed at $\theta = 2.5^\circ$ in Fig. 16 are due to a geometrical effect related to the parameters of the 3D converter cathode. At this angle the thickness of $^{10}\text{B}_4\text{C}$ crossed by the neutrons causes the results to be lower with respect to $\theta > 3^\circ$. Due to the coarser granularity of the performed scan, this effect was not experimentally appreciated. A finer angular scan for $2^\circ < \theta < 3^\circ$ is needed to measure this effect. Details of the simulation are provided in another paper that is presently under submission [43].
3.5.2. Efficiency as function of neutron wavelength $\lambda$

The efficiency of the detector was also determined as a function of neutron wavelength in the range $1 \cdot 10^{-10} \text{ m} < \lambda < 4 \cdot 10^{-10} \text{ m}$ accessible on EMMA. The results are shown in Fig. 17. A value of efficiency higher than 40% is obtained at $\lambda = 4 \cdot 10^{-10} \text{ m}$, which makes this technology competitive with other detectors for small angle neutron scattering (SANS) applications. A tilt angle of $\theta = 5^\circ$ has been set for this measurement.

3.6. Position resolution determination

As explained in Sect. 2.1, in order to increase the detection efficiency, the BAND-GEM detector must be tilted by few degrees. Due to this feature, a neutron trajectory can give signals in 2–4 adjacent gaps and thus more than one pad per event can collect charge. This is due to the probability $p$ of a neutron being absorbed in a single strip (each made of two boron layers). If $p$ is the absorption probability every time a neutron crosses a thin wall of a borated grid ($p$ only depends on the boron capture cross section and the angle at which the strip is crossed), then a probability density function can be constructed following the description in Fig. 18. The spatial resolution is therefore defined as the FWHM of the distribution of the joint probability $p$ of a neutron to be absorbed in either one of the two strips adjacent to a specific gap and to release by-products into this specific gap.

Analytically the probability density function $p(x)$ [53] can be written for the first three intercepted gaps as

$$p(x) = \begin{cases} 
p(GAP 1) 
p(p^2 - 3p + 2)(GAP 2) 
p(-p^3 + 3p^2 - 3p + 1)(GAP 3), 
\text{.... (GAP 4)} 
\text{....}
\end{cases}$$

which has first- and second-order momenta given by

$$\mu = \int_{\text{GAP}} x * p(x) \, dx = \int_{\text{GAP}} p(x) \, dx = \frac{-10p^3 + 36p^2 - 48p + 24}{-p^3 + 4p^2 - 6p + 4}$$
Fig. 18. BAND-GEM position resolution is defined as the FWHM of a probability density distribution of charge collection events in adjacent gaps.

Fig. 19. Measured BAND-GEM spatial resolution versus the tilt angle and comparison with calculation.

\[
\sigma^2 = \frac{\int_{GAP_1}^{GAP_n} (x - \mu)^2 \cdot p(x) \, dx}{\int_{GAP_1}^{GAP_n} p(x) \, dx},
\]

where GAP\(_n\) is the last gap that can be crossed by a neutron trajectory and depends on the incident angle. The FWHM of the \(p(x)\) distribution is

\[
\text{FWHM} = 2.35\sqrt{\sigma^2}
\]

and can be used as an estimate of the spatial resolution of the detector.

The results of the calculation along with measured FWHM values at different angles and for two neutron wavelengths are shown in Fig. 19. These were obtained by illuminating the detector with a pencil beam of neutrons (4 \(\times\) 4 mm\(^2\)). The measured resolution approaches that defined for the ideal case and does not depend on the neutron energy. The ideal case implies a precise alignment between the pads and the 3D converter system. The method adopted in order to guarantee the alignment within certain limits was described in Sect. 2.3. The slope variation of the curves present for \(\theta = 3^\circ\) is due
to the fact that a higher number of coated strips is crossed by the neutron beam (see the scheme shown in Fig. 18). Up to \(\theta = 3^\circ\), the number of coated strips intercepted by the neutron beam is a maximum of one, thus a maximum of two gaps can give a signal (i.e., the histogram of Fig. 18 would be narrower). A narrower distribution features a lower FWHM value. For \(\theta > 3^\circ\), the number of coated strips intercepted by a neutron trajectory becomes more than one, thus implying a broader signal distribution. These results are particularly important for SANS applications.

### 4. Conclusions and future perspectives

The BAND-GEM detector described in this paper is one of the most recent developments of neutron detectors based on complex converters: the boron layers are distributed in a number of grids composing a 3D converter, and a proper regulation of the field inside the converter ensures good charge collection. A feature of the 3D converter is that, if the whole detector is tilted by an angle \(\theta\) with respect to the direction of incoming neutrons, the thickness of \(^{10}\text{B}_4\text{C}\) crossed by the neutrons is increased by a factor \(1/\sin(\theta)\) so that the neutron “conversion” probability, and thus the detection efficiency, is enhanced. The detector was tested on the EMMA instrument at ISIS. A measurement of the relative charge extraction efficiency across the 3D converter resulted in values up to \(\eta_C = 67\%\). The efficiency \(\epsilon_{\text{GEM}}\) approaches 40% at \(\lambda = 4 \times 10^{-10}\) m for a tilt angle \(\theta = 5^\circ\). The spatial resolution measured for this angle is \(\sim 7\) mm and is independent of neutron energy. These and other features achieved with this new technology, make it an attractive candidate for small angle neutron scattering applications. Most SANS instruments (e.g., D22 at ILL [54] and Sans2d at ISIS [54]) are nowadays equipped with \(^3\text{He}\) tubes that are traditionally the most commonly used thermal neutron detectors. These detectors assure efficiency greater than 80% and spatial resolution on the order of 5 mm (depending on specific tube geometry), but their rate capability is limited to 30–50 kHz/tube. In addition, the exponential rise of the price of \(^3\text{He}\) makes it prohibitive to realize new instruments entirely based on \(^3\text{He}\) technology. The increase of neutron fluency expected in future spallation sources (like ESS) requires the development of new detectors and the one described in this paper belongs to this new detector family. The BAND-GEM technology is thus one of the candidates for installation (after further optimization) on small angle neutron scattering instruments such as LoKI, one of the first instruments to be installed at the European Spallation Source. Further steps will be the construction of a full detector module suitable for installation on LoKI [56].

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