I-BAND-GEM: a new way for improving BAND-GEM efficiency to thermal and cold neutrons

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Abstract. The BAND-GEM detector represents one of the novel thermal neutron detection devices that have been developed in order to fulfil the needs of high intensity neutron sources that, like ESS (the European Spallation Source), will start operation in the next few years. The first version of this detector featured a detection efficiency of about 40% for neutrons with a wavelength of 4 Å, a spatial resolution of about 6 mm and a rate capability in the order of some MHz/cm². The novelty of this device is represented by an improved 3D converter cathode (10 cm thick) based on ¹⁰B₄C-coated aluminum grids positioned in a controlled gas mixture volume put on top of a Triple GEM amplifying stage. The position where the neutron interacts in the converter depends on their energy and it was observed that the first version of the detector would suffer from an efficiency decrease for long (> 5 Å) neutron wavelength. This paper describes how the new 3D cathode allowed improving the detection efficiency at long neutron wavelengths while keeping all the benefits of the first BAND-GEM version.

1 Introduction

Neutron diffraction and spectroscopy experiments using thermal neutrons are the core activity at spallation neutron sources and up to now detection systems have made great use of ³He-based gaseous detectors. The ³He shortage [1] and the massive use of this gas in applications linked to homeland security have determined an exponential rise of 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 ³He, 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 [4]. The situation called for the development of large area and high-rate neutron detectors with a comparable detection efficiency to those of ³He but with a price ideally not exceeding 500 k€/m² and a spatial resolution between 1–10 mm. The BAND-GEM (Boron Array Neutron Detector) detector represents one of the established technologies able to fulfill the requirements of new high luminosity spallation sources [5]. This detector is based on the GEM technology [6–9] to detect neutron beams at high rate (> 1 MHz/mm²), giving the possibility to cover 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 [10–13]. Several GEM detectors for fast and thermal neutrons have been realized during the last years [14–33]. The first version of BAND-GEM detector was built and tested in 2016 [34] and although its results were promising, its performance could be further improved especially in the cold neutrons range (wavelength > 5 Å). This paper describes the construction,

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Fig. 1. Neutron conversion probability on the 3D converter for two different wavelengths.

test and results obtained by an improved version of BAND-GEM (named I-BAND-GEM) especially in the detection of long wavelength neutrons.

2 The I-BAND-GEM principle

The Boron Array Neutron Detector based on the GEM technology (BAND-GEM) described in [34] consists of a 3D converter cathode mounted on top of a Triple GEM and operated with a Ar/CO₂ 70%/30% gas mixture. The 3D converter is made of a stack of aluminum grids coated with 1.1 μm ¹⁰B₄C (with boron 99% isotopically enriched in 10-Boron [35,36]). Each grid is 3 mm high, has an overall area of 12 × 7 cm² and is composed of eleven strips 10 cm long, 3 mm high and 200 μm thick. The pitch between the strips is 4 mm and between each couple of grids there are 1 mm thick fiberglass spacers. Each of the grids is biased with a potential (distributed through a resistor divider) in such a way that the whole 3D cathode acts as a field cage [37]. Three standard GEM foils and a padded anode are placed on top of the borated grid stack. If the full detector is inclined (less than 10°) with respect to the incoming beam, neutrons are forced to cross the boron layers at grazing angles and are converted in charged products via the n(¹⁰B, ⁷Li)α reaction. 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 nuclear reaction occurring in the layer implies that the two charged particles (⁷Li and α) are emitted back to back with kinetic energies of the order of 1 MeV. It means that at least one of the charged products is likely to leave the ¹⁰B₄C layer and ionize the gas mixture in which the converter is placed. In order to get the signature of the neutron interaction, the primary electrons must be extracted out of the converter, multiplied by the Triple GEM stage and finally read-out by the padded anode. Some of the primary electrons are lost during their path and do not manage to reach the Triple GEM stage because of the particular shape of the 3D converter. The electron extraction efficiency from the neutron converter (η) decreases as a linear function of the distance from the Triple GEM [34]. If η is too low, the signal can be lost, thus lowering the detection efficiency. This issue is more pronounced for long wavelength neutrons (> 5 Å). Moreover, the ¹⁰B neutron absorption cross section increases linearly with the wavelength of the neutrons (it goes from 2233 barns at 1 Å to 22322 barns at 10 Å). This increase implies that cold neutrons have a higher probability to convert in the region that is the farthest away from the Triple GEM structure. In order to understand this effect in detail, a numerical simulation was performed. If p(z) represents the neutron absorption probability at a certain depth, its integral J(z),

$$J(z) = \int_0^z p(z') dz',$$

is directly proportional to the amount of neutrons that will be absorbed up to that specific depth z. Figure 1 shows the integral J(z) as a function of z for two different neutron wavelengths, 1 Å and 10 Å. In the case of λ = 1 Å it is clear that neutrons are absorbed almost uniformly over all the converter depth, while about 80% of 10 Å neutrons are absorbed for z < 40 mm, *i.e.* in the converter region far away from the Triple GEM structure. It is thus possible to conclude that neutrons with long wavelength convert mainly in the region where the charge extraction efficiency η has its minimum value.

The combination of these two competing effects implies a decrease of overall neutron detection efficiency at long wavelength. The charge extraction efficiency, especially far from the Triple GEM structure, must be augmented, in order to improve the detection efficiency. A single GEM foil was placed in the middle of the neutron converter stack to increase η as shown in fig. 2 where both BAND-GEM and I-BAND-GEM design are described.

Fig. 2. Layout of BAND-GEM (left) and I-BAND-GEM (right) detectors.

Fig. 3. Pictures of I-BAND-GEM assembly and of the padded anode used to detect signals.

The GEM foil (Middle-GEM) in the middle of the stack, with applied voltage from 250 V up to maximum 290 V, allows to multiply primary electrons produced close to the cathode by a factor ranging from 1.5 to 3 thus increasing η for the region farthest from the Triple GEM and enhancing the overall detection efficiency.

2.1 I-BAND-GEM construction

The dimensional and physical parameters of the grids used for the realization of the 3D converter of I-BAND-GEM (see table 1) are the same used for BAND-GEM construction [34].

The main differences are the thickness of the $^{10}\text{B}_4\text{C}$ coating, it was increased to $0.65\ \mu\text{m}$ in order to further improve the neutron absorption probability, the presence of the Middle-GEM (that has an active area of $50\ \text{mm} \times 50\ \text{mm}$) and the design of the padded anode (compared to the one used in [34]). Figure 3 shows two pictures of the detector assembly and one of the read-out. This is constituted by 128 square pads with an area of $4\ \text{mm}$ (x -direction) $\times$ $3\ \text{mm}$ (y -direction) defining an active area of about $52\ \text{mm}$ (x) $\times$ $33\ \text{mm}$ (y). The pads were positioned on the side of the detector provided with the Middle-GEM. The signal of each pad is routed to a different channel of a CARIoca [38] chip whose connector is located on the back of the read-out anode board. The Low Voltage Discriminated Signal (LVDS) signals of each CARIoca channel are sent to an FPGA motherboard [39] located off the detector. It provides a real time processing of the signal used for the on-line monitoring of the neutron beam. The bias voltage to the three GEM foils is given by means of a custom designed NIM Module (HVGEM) [40] directly interfaced with a control PC. The neutron converter is biased by a module (CAEN A1526 [41]) that is able to deliver up to 15 kV.

Table 1. Geometrical and electrical parameters of the BAND-GEM and the I-BAND-GEM detectors.

	BAND-GEM	I-BAND-GEM
Strip pitch	4 mm	4 mm
Grid thickness	3 mm	3 mm
Spacer thickness	1 mm	1 mm
Number of walls per grid	11	11
3D converter dimensions	100 mm (x) · 50 mm (y) · 96 mm (z)	100 mm (x) · 50 mm (y) · 96 mm (z)
Strip thickness	200 μm	200 μm
Grid bulk material	Aluminium Al5754	Aluminium Al5754
B ₄ C resistivity	696 $\Omega\text{ cm}$	696 $\Omega\text{ cm}$
¹⁰ B ₄ C thickness on Al strips	0.55 μm	0.65 μm
Tilting angle used for $\eta_C(z)$ measurement	90°	90°
Tilting angle used for efficiency and spatial resolution measurements	5°	5°
Triple GEM voltage (V_{GEM})	900 V	900 V
Induction field (E_I)	5 kV/cm	5 kV/cm
Transfer field 1 (T_1)	3 kV/cm	3 kV/cm
Transfer field 1 (T_2)	3 kV/cm	3 kV/cm
Transfer drift field	1.5 kV/cm	1.5 kV/cm
$V_{\text{Top-3DC}}$	3.3 kV	3.3 kV
$V_{\text{Middle-GEM-Top}}$	//	8.5 kV
$V_{\text{Middle-GEM-Bottom}}$	//	8.77 kV
V_{Cathode}	14.0 kV	14.0 kV

3 The I-BAND-GEM performance

3.1 Experimental Setup at EMMA, CRISP beam lines at ISIS and at the TREFF beam line at FRM2 (include measurements methods)

The I-BAND-GEM detector prototype was tested at the neutron beam line TREFF at the FRM-II research reactor in Garching (Germany) and at the EMMA and CRISP instruments of the ISIS spallation neutron source in Didcot (United Kingdom). TREFF is a beam line featuring a monochromatic neutron beam with a wavelength of 4.74 Å [42] and a tunable flux between $10^3\text{ n/cm}^2\text{s}$ and $10^6\text{ n/cm}^2\text{s}$. The collimation system allows getting very narrow beam profiles, down to $500\text{ }\mu\text{m} \times 500\text{ }\mu\text{m}$. The EMMA and CRISP are instruments at the ISIS Target Station 1 [43] and operate at 50 Hz (EMMA) and 25 Hz (CRISP), respectively. This difference allows EMMA to have a neutron beam ranging from 1 Å to 4 Å and CRISP from 1 Å to 10 Å, each with a maximum flux of about $10^6\text{ n/cm}^2\text{s}$. This is due to the neutron beam structure in a pulsed source where all neutrons in a bunch are generated at the same T_0 . Long wavelength neutrons have a lower velocity with respect to short wavelength neutrons and thus the time they spend to reach the instrument (*e.g.*, the sample position in CRISP) is longer. The CRISP shutter is designed in order to allow every two bunches to enter the instruments: this allows the possibility to avoid superimposition of long wavelength neutrons belonging to bunch number i with short wavelength neutrons belonging to bunch number $i + 1$ that is generated later in time. This implies that CRISP operates at half value of the nominal 50 Hz frequency, *i.e.* 25 Hz, but can explore a wider wavelength range.

The aim of the measurements was to determine η as a function of converter depth, the overall detection efficiency ε and the spatial resolution as a function of the neutron wavelength. At TREFF, measurements with a $2 \times 2\text{ mm}^2$ monochromatic beam of 4.74 Å neutrons entering orthogonally with respect to the strips ($\theta = 90^\circ$) allowed to study the η of the I-BAND-GEM while measurements with a $4 \times 4\text{ mm}^2$ monochromatic neutron beam entering at $\theta = 5^\circ$ were done to determine the efficiency of the I-BAND-GEM detector relatively to a calibrated ³He detector. The measurements at ISIS (performed with a $4\text{ mm} \times 4\text{ mm}$ beam) were done to determine the detector efficiency as a function of neutron wavelengths between 1 Å and 4 Å (on EMMA [44]) and between 1 Å and 10 Å (on CRISP [43]).

Fig. 4. On the left a footprint of the beam entering the I-BAND-GEM detector at $\Theta = 90^\circ$ is shown. The color scale represents the integrated counts in 120 seconds. The right panel shows the comparison of relative charge extraction efficiency $\eta_C(z)$ for I-BAND-GEM and BAND-GEM devices. The Middle-GEM was positioned at approximately $z = 45$ mm for the I-BAND-GEM only.

At ISIS the efficiency was determined relatively to a standard calibrated beam monitor and using the standard Time-Of-Flight technique as described in [34].

3.2 Improvement of charge extraction efficiency η_C

One of the most important parameters to be determined when working with a 3D converter that operates also as a field cage is the capability of extracting the primary charge that is released by neutron capture products (either alphas or Li ions). The electron extraction depends on the applied electric field and the position of the neutron absorption in the field cage. To test the latter dependency, we operated the detector at 90° with respect to the incoming neutron beam, performing a z -direction scan. In this test the neutrons are entering in the detector through thin window introduced in the detector only to do this test ($80 \text{ mm} \times 100 \text{ mm}$, with $z = 80 \text{ mm}$ the maximum accessible z). Figure 4(left) shows how the beam footprint results for one of such measurements at 90° : the neutron beam (coming from the bottom in the figure) is slowly attenuated along the y -direction; the consequent deposited energy shows itself as a long and narrow footprint on the pad plane (x -direction). The integrated (over 300 s) counting rate $I_{\text{GEM}}(z)$ was recorded for each z -position. The relative charge extraction efficiency η_C is defined as $\eta_C(z) = I_{\text{GEM}}(z)/I_{\text{GEM}}(z = 80 \text{ mm})$ and shown in fig. 4(right) for both the BAND-GEM and I-BAND-GEM. While for BAND-GEM the curve η_C vs. z is linear and decreases with the distance from the Triple GEM (towards negative z), for I-BAND-GEM the same curve shows a stepwise increase in correspondence of the position of the Middle-GEM (about $z = 45 \text{ mm}$). The Middle-GEM is enhancing the extraction efficiency: the 3D converter is practically divided in two volumes with approximately the same relative charge extraction efficiency.

Both the results obtained for BAND-GEM and I-BAND-GEM agree with the results of a numerical calculation performed using the ANSYS and Garfield++ software [45]. Ideally η_C has to be as close as possible to 1, providing uniform charge extraction efficiency throughout the depth of the detector.

3.3 Improvement of neutron detection efficiency

In order to directly compare the performance of the two detectors, an efficiency measurement of the I-BAND-GEM was performed applying the same method used for the BAND-GEM in [34]. The efficiency of the detector was determined as a function of neutron wavelength in the range accessible on EMMA, namely $1 \text{ \AA} < \lambda < 4 \text{ \AA}$. In addition, for the I-BAND-GEM only, the results of the measurement at TREFF for $\lambda = 4.74 \text{ \AA}$ were added. The tilt angle for both measurements was $\Theta = 5^\circ$. The comparison of the resulting efficiencies (see fig. 5) shows that I-BAND-GEM has an efficiency of about 10% higher in this range of wavelengths. This result shows the use of the Middle-GEM implies a better performance, not only at long neutron wavelengths but also at short ones. Also in this case the obtained results are in agreement with the numerical calculation performed using IDL+ANSYS+Garfield++ software [45].

Fig. 5. Comparison of the I-BAND-GEM and BAND-GEM efficiency as a function of neutron wavelengths from 1 Å to 4.74 Å, in the simulation and in the experimental data.

Fig. 6. I-BAND-GEM efficiency as a function of neutron wavelengths from 1 to 10 Å, in the simulation and in the experimental data.

3.4 Measurement of the neutron detection efficiency and the spatial resolution at long neutron wavelengths

On CRISP we measured the I-BAND-GEM efficiency and spatial resolution at neutron wavelengths in the range between 1 Å and 10 Å. The same tilting angle of $\Theta = 5^\circ$ was set for this measurement too. The efficiency was determined using the Time-Of-Flight technique and relatively to a standard calibrated neutron beam monitor with efficiency of about 0.6% at $\lambda = 1$ Å as in [34]. The results are shown in fig. 6. They show that:

- up to 5 Å neutrons CRISP results agree with EMMA and TREFF measurements as expected;
- the neutron detection efficiency reaches a plateau of about 50% for $\lambda > 5$ Å. This result is in agreement with the IDL+ANSYS+Garfield++ simulation. It confirmed that, the increase of the charge extraction efficiency from the 3D-converter volume provide a constant efficiency up to $\lambda = 10$ Å.

The CRISP measurement also allowed determining the spatial resolution of the detector by measuring the FWHM of the reconstructed neutron profile in the two directions, across (x) and along (y) the 3D converter gaps (see fig. 2). The momenta of the spatial neutron distribution were calculated following the same methods described in [34].

The FWHM X measured across the gaps has a larger value (about 6.5 mm) than those measured along the gaps, which ranges from 3.5 up to 4.5 mm (fig. 7). This is due to the fact that the x -direction is influenced by the tilting angle that instead does not have any effects on the other direction. The FWHM X shows a slight decrease at long wavelengths. Long wavelength neutrons have a very high probability to interact with the first $^{10}\text{B}_4\text{C}$ layer and as a consequence to give signals whose size is limited to the pads corresponding to a single gap. On the other hand, short wavelength neutrons have a larger probability to give signals on pads corresponding to two or more gaps. The fact that long wavelength neutrons interact with the very first B_4C layers also implies that the corresponding charged products will release energy in regions close to the cathode: the primary charge has to drift along all the 3D converter depth

Fig. 7. Measurement of the FWHM across gaps and along gaps of the neutron distribution using I-BAND-GEM. The details of the methods used for FWHM determination are described in [34].

and a higher fraction of the charge is likely to be lost on the grid walls, thus narrowing the whole electronic cloud. The effect on the spatial resolution is a further shrinking of the recorded spot in this direction. On the other hand, the FWHM Y increases at longer wavelengths. This can be explained by considering that the dominant effect in defining the primary cloud dimension in this direction is the transverse diffusion: electron clouds starting close to the cathode will thus experience a larger diffusion than those starting close to the Triple GEM.

4 Conclusions and future perspective

The I-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 setting of the field inside the converter, together with the insertion of an amplification stage, ensures good charge collection. A feature of the 3D converter is that, if the whole detector is tilted by an angle θ 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 is enhanced and thus the detection efficiency. Moreover, the presence of the Middle-GEM, acting as an electron amplification stage, enhances the charge extraction probability also in the lower efficiency parts of the 3D converter. The detector was tested on the EMMA and CRISP instruments at ISIS and on the TREFF beam line of the FRM-II reactor. A relative charge extraction efficiency across the 3D converter of $\eta_C = 80\%$ was obtained. This allowed to get efficiency ε_{GEM} approaching 50% at $\lambda > 5 \text{ Å}$ for a tilt angle $\theta = 5^\circ$ and neutron energy independent spatial resolution of $\sim 6.5 \text{ mm}$ and 5 mm across and along the 3D-converter gaps, respectively. These and other features achieved with this new technology make it an attractive candidate for Small Angle Neutron Scattering (SANS) applications. Most of the SANS instruments (*e.g.*, D22 at ILL and Sans2d at ISIS [46]) are nowadays equipped with ^3He tubes assuring efficiency larger than 80%, spatial resolution in the order of 5 mm (depending on specific tube geometry) and rate capability limited to $30\text{--}50 \text{ kHz/tube}$. The increase of neutron fluency expected in the future spallation sources (like ESS) joint to the exponential rise of ^3He price required development of high rate ^3He -free detectors as the one described in this paper. The maximum rate achievable with I-BAND-GEM (measured at the Orphee reactor of the LLB-institute in Saclay [47]) was about 1 MHz/cm^2 . This topic is not treated here since it is the subject of another paper that will be published in the future [48].

The I-BAND-GEM technology is thus one of the candidates for installation (after further optimization) on SANS instruments such as LoKI, one of the first instruments to be installed at the ESS. Further steps will be the construction of a full I-BAND-GEM detector module suitable for installation on LoKI [49]. On the other hand further R&D work will be performed in the future in order to further increase the detection efficiency: for example the effect of use of more GEM foils in the grid stack will be tested.

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Author contribution statement

Gabriele Croci, Andrea Muraro, Enrico Perelli Cippo, Giovanni Grosso, Giuseppe Gorini contributed equally to this work.

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