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Characterization of multilayer Thick-GEM geometries as ^{10}B converters aiming thermal neutron detection

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Abstract. Boron-based thermal neutron detectors have recently regained some attention from the instrumentation community as a strong alternative to helium-3 detectors. From the existing concepts exploiting boron layers in position sensitive detectors, the Cascade [1] is the one that takes full advantage of the 2D capabilities of gaseous detectors, with the position resolution not limited by the architecture of the detector. In this work, a proposal for the Cascade detector, based on Thick-GEMs is presented, together with some preliminary studies of the suitable pitch that optimizes the neutron conversion efficiency, while keeping the collection efficiency intact. The characterization of Thick-GEM prototypes produced in Brazil with hole pitch from 0.75 to 3 mm shows that these devices already present a stable performance at low gains, also resulting in fair energy resolution, when cascaded with a standard Kapton™ 50 µm GEM. Results of the first attempts of boron film depositions with Ion Beam Assisted Deposition and characterization by Ion Beam Analysis are also presented.

1 Introduction

Helium-3 has been for many years the most used thermal neutron converter in large detectors due to its high absorption cross section. Its recent unavailability has been well reported (e.g.: [2]) and triggered an intense research to find alternatives, turning the attention of detector developers back to boron-10.

Boron is in the solid state at NPT presenting a challenge in its deposition on surfaces, with a reasonable thickness. In addition, when increasing the thickness of the boron layer to improve the final detector efficiency, the self-absorption of the products of the nuclear reaction starts to play an important role. Therefore, there is an optimal thickness that maximizes the detection efficiency.

The use of many layers has been studied through simulations ([3, 4]) and confirmed by this work (figure 1), where it can be seen that the efficiency increases with the number of layers and the optimal thickness decreases. Furthermore, for more layers, the optimal efficiency becomes more dependent on the thickness of each layer. The deposition method must be able to deposit boron layers between 1 and 2.5 µm.

Several multi-layer geometries have already been developed, such as Multi-grid [5], Inclined detector [6], Jalousie [7] or Cascade [1] with efficiencies very close to those achieved with ^{3}He-based detectors. However, most of them achieve limited position resolutions due to the geometry of the neutron absorbers. Only the Cascade concept is able to fully exploit the position capabilitiy of a micropattern gaseous detector. However, for the stages dedicated to neutron absorption, working at unity charge gain, a simpler and more mechanically robust structure can be used. Even a detector with less stability against electrical discharges at high gains, can operate quietly when such a low gain is used.

In this work, a proposal based in the Cascade concept for the use of many boron layers is described, using Thick-GEMs (THGEM) as boron-coated neutron converters and electron transporters, together with a standard GEM-based charge amplification stage, as depicted in figure 2.

The THGEM was introduced in 2004 [8]. It is based on the Gas Electron Multiplier concept [9], with 0.5 mm holes drilled through a copper-coated FR4 board with a thickness of 0.5 mm. With the board immersed in a suitable gas mixture, by applying a high voltage between the two sides of the board, the electric field inside the holes is strong enough to multiply the primary electrons generated by the interaction of the ionizing radiation with the gas. THGEMs (like GEMs) can be used in a cascaded geometry to achieve higher gains at a more stable operation. For more details concerning GEM and THGEM operation see [10, 11]. By depositing ^{10}B films on both sides of a THGEM, the electrons generated near the surface by the absorption of the energy of the conversion reaction in the gas can be transported through several absorber layers and will be available for a final multiplication stage.

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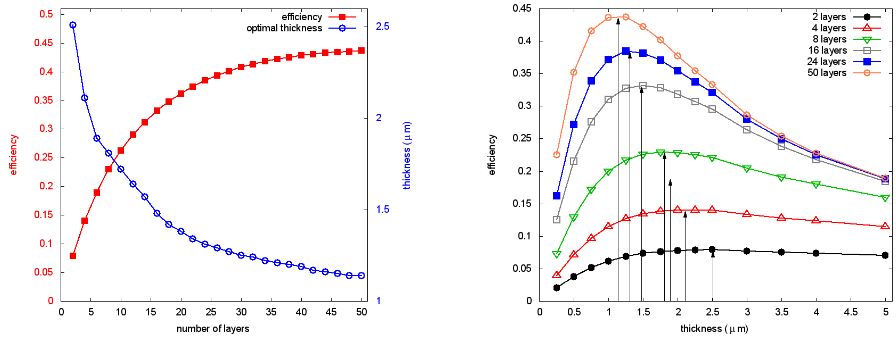

Figure 1. Simulations confirming the results of [3, 4]. Left: By increasing the number of layers, the final efficiency of the detector increases, whereas the optimal thickness decreases. Right: When the number of layers increases, the optimal thickness plateau becomes narrower. Simulation for 1.8 Å neutrons, without any energy threshold for particles leaving the ^{10}B layers.

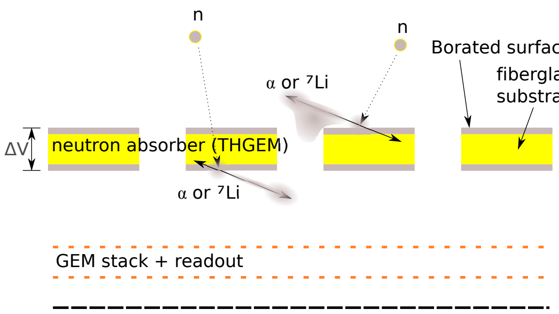

Figure 2. The THGEM based Cascade [1] concept: ^{10}B is deposited on both sides of the THGEMs that work as neutron converters and, while operating at unity gain, transport the electrons generated by the energy deposited by the conversion reaction to the multiplication stage. Only one THGEM layer is represented in the figure.

2 Experimental setup

The optical transparency of the THGEM also has an effect on the efficiency of the neutron converter. In fact, the surface available for ^{10}B deposition can increase from 60 % for a pitch of 0.75 mm up to 97 % for a pitch of 3 mm, considering a diameter of 0.5 mm for the holes. However this has a cost in the THGEM collection efficiency. It was understood soon after the introduction of the GEM that at high drift fields, the electric field inside the holes is not strong enough to push all the electrons in and some are lost on the THGEM surface, reducing the collection efficiency [12]. This effect increases with the drift field or when the distance between them becomes larger. Therefore, the hole pitch cannot increase infinitely, especially because the THGEMs serving as neutron converters will operate at very low gain, requiring low drift and transfer electric fields. Furthermore, the drift and transfer fields must be above the recombination threshold. All these features are competing with each other and a compromise between total collection efficiency, with maximum neutron conversion efficiency must be found by studying the THGEM behavior as a function of the hole pitch.

A THGEM prototype segmented in four sectors has been designed and produced using standard printed circuit board techniques. The four sectors had 0.75, 1, 2 and 3 mm hole pitch. The holes were drilled directly across the copper layers and the FR4, without any clearance between the copper and the hole. Different geometries were used in a chamber filled with an Ar/CO_2 (90/10) mixture at atmospheric pressure in an open flow of 6 L h^{-1}. The charge readout was made either from the bottom electrode of the THGEM, with a reversed induction field to avoid effects due to limitations in extraction efficiency, or with a $10 \times 10\,cm^2$ pad readout consisting of a matrix of 10×12 rectangular pads. All the high voltage channels in the detector were biased independently. The drift gap was 6.2 mm thick.

3 Results

To assess the quality of the THGEMs produced, the gain of each sector was measured using an X-ray source (Amptek Mini-X, with a silver target) to generate a primary current. Figure 3 shows the gain as a function of the voltage across the holes for each of the four sectors for a single and double geometry. The gain curve for a standard single GEM is also plotted to give an idea of the scaling in voltage. The drift electric field was set to optimize the collection efficiency. The induction field was 600 V/cm and the transfer field for the double geometry was the same as the drift field. The transfer and induction gaps were 2 mm. As expected, no dependence of either the gain at each voltage or the maximum gain of each sector on the hole pitch was observed. The maximum gains achieved in single and double mode were around 150 and 1000, respectively. A clearance between the copper layer and the holes should increase the maximum gain, however, it is clear that the operation at gains around 1 will be stable.

To measure the collection efficiency, the same X-ray generator was used. A reversed induction field of 600 V/cm was applied, to allow collecting the charge at the bottom electrode of the THGEM. If the THGEM gain is kept constant, the current at the bottom electrode is proportional to the collection efficiency. Figure 4 shows the

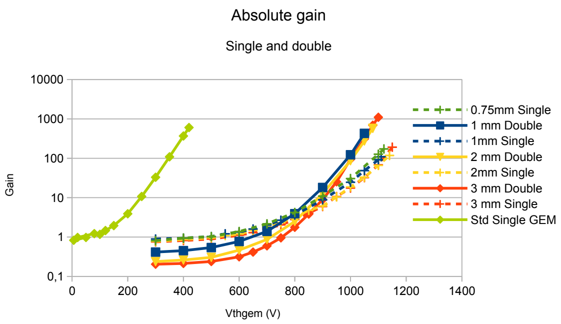

Figure 3. Gain curves for single and double geometries in each of the four sectors. The gain curve for a standard GEM is also plotted for comparison.

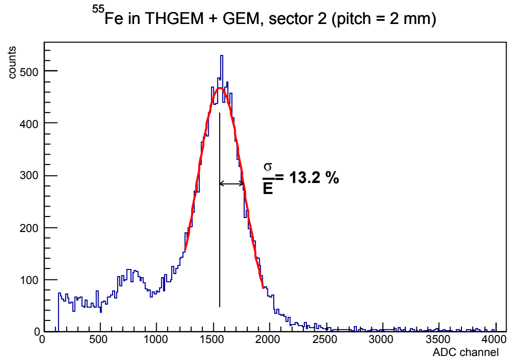

Figure 5. Pulse heigh distribution obtained with a ^{55}Fe radioactive source. On the left of the 5.9 keV peak, the argon escape peak is clearly visible.

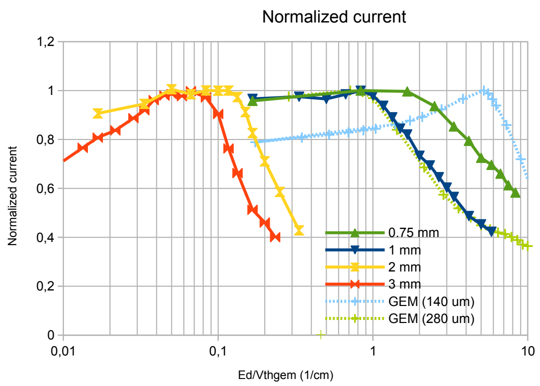

Figure 4. Current at the bottom electrode as a function of the drift electric field, normalized to the voltage across the holes of the THGEM. Each curve was normalized to its maximum value to have plateaus near 1, proportional to the collection efficiency.

current at the bottom electrode normalized to 1, as a function of the drift electric field (E_d) normalized to the voltage across the holes (V_{thgem}). For a comparison, the curves for two standard GEMs with pitch 140 μm and 280 μm are also plotted. The value of E_d/V_{thgem} at which the collection efficiency starts to drop depends on the hole pitch and is higher for smaller pitch. In the case of 2 and 3 mm pitch, this value is around 0.1 cm^{-1}, meaning that to operate at unity gain (between 200 and 400 V across the holes, according to figure 3), the drift field would have to be very low (20 to 40 V/cm) leading to higher difusion, and in the limit, to primary electron loss due to recombination.

A standard GEM with a thickness of 50 μm, holes with 70 μm diameter in the copper and a pitch of 140 μm was used as second multiplication stage to achieve a gain around 5000, high enough to provide energy spectra. The THGEM was operated at a gain around 100. The spectrum in figure 5 was taken from a ^{55}Fe radioactive source (5.9 keV) with a hole pitch of 2 mm. The energy resolution is 13.2 %. When a smaller pitch was used, the energy resolution improved, probably because the primary electron cloud spreads over more holes, reducing the influence of the non-uniformities in their size. Nevertheless, this energy resolution is enough to allow a good discrimination of the signals when detecting thermal neutrons.

4 Boron deposition and ion beam analysis

The deposition of boron on copper surfaces poses a number of issues that have been studied and reported in other works (for example [13]). The ion beam assisted deposition (IBAD) technique [14] was used to prepare thin boron films on copper substrates. The IBAD apparatus used consists of a Kaufman-type ion gun and an electron-beam evaporator, adapted to a vacuum chamber. The base pressure in the vacuum chamber was about 7×10^{-5} Pa and 99.9 % pure boron evaporated using the electron-beam evaporator was deposited on a chemically cleaned copper substrate. The angle of incidence of the evaporated boron atoms on the substrate surface was 45° and the deposition rate of boron measured with a quartz crystal sensor was 0.054 nm/s. During the deposition, the substrate surface was normally exposed to an argon ion beam generated by the ion gun (the ion energy of 200 eV and the ion current density of 0.12 mA/cm2) to improve the adherence and densification of the film. The working pressure was around 2.4×10^{-2} Pa.

Three different Ion Beam Analysis (IBA) techniques for material characterization were performed on the same sample spot to check for the thin film composition. The selection of techniques was made regarding the complementarity of obtained information for the specific case of this study: the boron concentration was determined by Nuclear Reaction Analysis (NRA) using the $^{11}B(p,\alpha_0)^{8}Be$ nuclear reaction [15]; the oxygen content on the sample was determined by Elastic Backscattering Spectrometry (EBS); and Rutherford Backscattering Spectrometry (RBS) was used to provide additional information on the depth profile of elements. For the EBS modeling, the cross-section for the $^{16}O(p,p)^{16}O$ elastic scattering provided by SigmaCalc was used [16]. The set of spectra was processed self-consistently [17, 18], which means that all spectra were fitted simultaneously by the minimization of a χ^2 function that takes into account all spectra. The sample model that best describes all available data (minimum χ^2) is elected

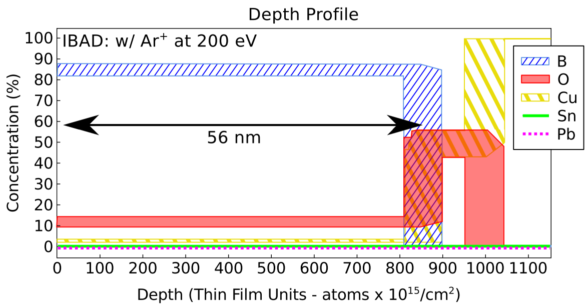

Figure 6. Element depth profile of the deposited boron film. Equivalent thickness for the boron film is 56 nm. Line thickness represents the calculated uncertainty.

to represent the sample. For a deeper description of the self-consistent approach, see Ref. [18].

Figure 6 presents the sample depth profile of elements, where the depth referred to the sample surface is expressed in 10^{15} at/cm^2 units. This model for the sample was obtained using the MultiSIMNRA software [18, 19], and the thickness of the lines represents the uncertainty obtained by a Monte-Carlo calculation to explore solutions with statistical significance on variations of the objective function. It is possible to observe a low-concentration of oxygen in the film, and a higher-concentration in the interface between the boron film and the copper substrate, suggesting the oxidation of the substrate surface prior the boron deposition. Trace-contaminants (tin and led) in low quantities (not visible in figure 6) were also found in the substrate, probably due the PCB manufacturing process.

5 Conclusions

The idea for a thermal neutron detector based in the Cascade concept, using cost effective THGEMs as boron-coated neutron converters and electron transporters was presented. The advantages of the THGEM with respect to the GEM are its mechanical robustness and cost effectiveness for large scale production.

Different distances between holes (pitch of 0.75, 1, 2 and 3 mm) were tested to determine a compromise between a larger area fraction covered with boron and a high collection efficiency. For the 3 mm pitch, the low drift electric field (around 20 V/cm) required to keep high collection efficiency is very close to the recombination threshold. The maximum gas gain (above 100) and energy resolutions ($\sigma \sim 13\,\%$) achieved are well within what is expected and needed for the operation of the detector. The position resolution of this system is dominated by the range of the conversion reaction products in the gas, the hole pitch of the THGEMs and the electronics used for charge collection in the anode. The range of the conversion products can be reduced by increasing the gas pressure in the detector. By reducing the hole pitch accordingly, the position resolution can be reduced down to less than 1 mm, with a cost in the detection efficiency.

Regarding the boron deposition, the IBA performed in the first samples made with IBAD reveals that the thickness of the boron film (56 nm) is still very small, compared to the $\sim 2\,\mu$m needed. Further depositions with a higher deposition rate and longer deposition times are foreseen to evaluate the limitations of this technique for larger thickness. Other deposition techniques are under study and will be tested in the near future.

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