Large Size GEM for Super Bigbite Spectrometer (SBS) Polarimeter for Hall A 12 GeV program at JLab

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Abstract

We report on the R&D effort in the design and construction of a large size Gas Electron Multiplier (GEM) for the Proton Polarimeter Back Tracker (BT) of the Super Bigbite Spectrometer (SBS) in Hall A at Thomas Jefferson National Laboratory (JLab). The SBS BT GEM trackers consist of two sets of five large GEM chambers of size $60 \times 200 \text{ cm}^2$. The GEM chamber is a vertical stack of four GEM modules, each with an active area of $60 \times 50 \text{ cm}^2$. We have built and tested several prototypes and the construction of GEM modules for SBS BT is ongoing. We describe in this paper the design and construction of the GEM module prototype as well as the preliminary results on performance from tests carried out in our detector lab and during test beam at Fermi National Laboratory (Fermilab).

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1. Introduction

In 2014, Jefferson Lab [1] will complete the 12 GeV upgrade of its Continuous Electron Beam Accelerator Facility, (CEBAF) which will allow outstanding study of nucleon structure in terms of form factors (FFs), transverse momentum distributions (TMDs), generalized parton distributions (GPDs) and structure functions in the valence quark region. CEBAF will be capable of delivering longitudinally polarized electron beams at an intensity of up to $85 \mu\text{A}$, which corresponds in some experiments to luminosities of $10^{39} \text{ electron/s-nucleon/cm}^2$. The SBS apparatus [2] in Experimental Hall A combines a high performance and large acceptance detector package (with an active area of $\sim 1 \text{ m}^2$) in an open geometry configuration with a dipole magnet located close to the target to provide a relatively large solid angle up to 75 msr for experiments to run at the largest luminosity possible. The SBS detector package can be arranged in specialized configurations to meet the needs of a number of highly-ranked experiments for the 12 GeV program, namely G_E^n , G_E^p and G_M^n [2].

The SBS, however, requires very high counting rate detectors to cope with a large background rate. Background

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29 rates as high as $400 \text{ kHz} / \text{cm}^2$ [2] are expected in its Front Tracker (FT), the closest to the target, for experiments
 30 such as G_E^p for such high luminosity. Moreover, the small field integral (2-3 Tesla-m) of the magnet means that one
 31 needs an angular resolution of 0.3 mrad [2] to achieve a momentum resolution below 1% with the small bend angle
 32 of incoming protons at a momentum of 8 GeV/c. With the FT located at about 70 cm from the target, in order to
 33 achieve this level of precision measurement, detectors with spatial resolution of the order of $70 \mu\text{m}$ must be used.
 34 GEM technology [3] has been adopted for the tracking systems of SBS to meet these challenges. The GEM
 35 technology permits large area detectors with high counting rate capabilities, exceeding to 2.5 MHz/cm^2 [4], and
 36 excellent spatial resolution of around $70 \mu\text{m}$ [5]. The detector group at the University of Virginia (UVa) is leading
 37 the design and fabrication of SBS BT GEM chambers for the SBS Polarimeter. In this paper, we report on the effort
 38 to design, build and characterize the SBS BT GEM modules.

39 **2. Large area GEM Trackers for SBS Polarimetry**

40 **2.1. Layout of the SBS proton arm for GEp (5) experiment.**

41 The most demanding SBS experiment, GEp (5) [6], is an ambitious physics program to measure the ratio of electric
 42 and magnetic elastic FFs of the proton at a 4-momentum transfer (Q^2) up to 12 GeV^2 . For this experiment, the SBS
 43 will be configured to detect the recoil proton and measure its polarization. As such, the SBS requires three GEM
 44 trackers, the FT, the Second Tracker (ST) and the Third Tracker (TT). The ST and TT constitute the Back Tracker
 45 (BT). Figure 1 shows the layout of the proton arm of the SBS for the GEp (5) experiment and one SBS BT GEM
 46 chamber. The FT is used to measure, with high precision and in a large background environment, the momentum
 47 and direction of the recoil protons from the electrons scattering off the target. It is made of six large ($40 \times 150 \text{ cm}^2$)
 48 GEM chambers. Each FT chamber is a vertical stack of three GEM modules, with an active area of $40 \times 50 \text{ cm}^2$.

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 50 Figure 1: (Left) layout of Super Bigbite Spectrometer for the GEp (5) experiment; (right) layout of SBS BT GEM
 51 chamber. The chamber is composed of 4 GEM modules in a vertical stack.

52 The FT GEM modules are being designed and fabricated by INFN-Roma and INFN-Catania in Italy [7].
 53 The ST and TT are combined with two CH₂ analyzer blocks for proton polarimetry. Proton polarimetry technique
 54 allows the determination of the proton FF ratio by the method of polarization transfer from the measurement of the
 55 ratio of the longitudinal and transverse components of the proton spin polarization. The transverse polarization of
 56 the recoil proton is measured from the azimuthal asymmetry after rescattering in one of the two CH₂ analyzer
 57 blocks. The polar and azimuthal angles of the rescattered proton are measured in the tracker downstream of the
 58 analyzer block, with respect to the angles measured by the upstream tracker [2].

59 Each SBS BT GEM chamber is a vertical stack of four GEM modules, each with an active area of $60 \times 50 \text{ cm}^2$. A
 60 sketch of a SBS BT chamber is shown at the right hand side of Figure 1. A total of 40 modules (of $60 \times 50 \text{ cm}^2$) are
 61 required for 10 SBS BT GEM chambers ($60 \times 200 \text{ cm}^2$). The R&D, prototyping and the construction of the SBS
 62 BT GEM modules is done at UVA.

63 2.2. Design of the SBS Back Tracker GEM module

64 The first two SBS BT GEM prototypes have an active area of $50 \times 50 \text{ cm}^2$ whereas in the final design for the SBS,
 65 the SBS BT GEM modules have a larger active area of $50 \times 60 \text{ cm}^2$ in order to improve further the acceptance of
 66 the double polarimeter. The results reported in the present paper mainly concerns the design and extensive tests
 67 carried out with the $50 \times 50 \text{ cm}^2$ SBS BT GEM prototype but remain equally valid for larger production modules
 68 for BT chamber. The picture on the left of Figure 2 shows the first SBS BT GEM prototype. The sketch on the right
 69 of Figure 2 is a cross sectional view of the SBS BT GEM module. The SBS BT GEM module design is based on
 70 R&D work previously done on GEM detectors for the COMPASS experiment [4, 5] at CERN and for the Muon
 71 Tomography project [8] at the Florida Institute of Technology (FIT).

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 73 **Figure 2: (Left) SBS BT GEM prototype; (right) cross section of the SBS BT GEM module.**

74 It consists of a 3 mm ionization gap between the drift cathode and the top GEM foil in the stack of three GEM foils.
 75 The GEM foils are separated from each other by a 2 mm transfer region and provide three stages of gas avalanche
 76 amplification of the primary ionization. This detector configuration with 3 GEM foils for the electron amplification
 77 is referred to as Triple-GEM detector. The drift of the electron cloud from the last GEM foil to the flexible readout

board, located 2 mm below the GEM stack, induces signals in the 2D Cartesian readout strip layers. The design is optimized to operate at a rate as high as 1 MHz / cm² while providing excellent spatial resolution of 70 μm with a stable and non-flammable Ar/CO₂ (70/30) gas mixture [4,5]. The active area of the SBS BT GEM module is, however, more than three times larger than COMPASS or FIT Triple-GEM detectors. Because of their large size, the foils used for the SBS BT GEM modules are fabricated at the CERN Printed Circuit Board (PCB) workshop using the single mask technique [9] developed at CERN for large area GEM.

A GEM foil for a SBS BT GEM prototype is shown in the top left picture of Figure 3. The 5 μm thick Cu electrode on the top side of each GEM foil is segmented into 24 high voltage (HV) sectors of roughly 100 cm², (30 HV sectors for the 50 × 60 cm² production modules). The GEM foils and the drift cathode are stretched and glued onto supporting frames made of the fiberglass-reinforced epoxy material Permaglas¹. The frames have a grid of 300 μm wide spacers to maintain a uniform gap (therefore a uniform electric field) between the layers after assembly.

Figure 3: Components of SBS BT GEM module and a few clean room assembly steps.

Pictures of the frames are shown at the bottom left and center of Figure 3. The two horizontal sides of the supporting frames are narrow, with 8 mm widths, to minimize the dead-to-active area ratio when four modules are

¹ from Permal, distributed by Resarm Engineering Plastics in Belgium, <http://www.resarm.com>

combined into one SBS BT GEM chamber as shown in the right picture of Figure 1. The wider (30 mm) vertical sides of these frames provide room for gas distribution holes and high voltage lines, as well as extra support for mechanical tension of the GEM foils. A GEM foil with the copper stripped off of one side is used as the cathode foil to allow for a simple but efficient gas flow throughout the entire sensitive volume of the detector. The 2D Cartesian readout board, based on the COMPASS GEM readout design, and fabricated using the same copper-clad Kapton material as for the GEM foils, consists of two sets perpendicular strips (top and bottom), with 400 μm pitch. The top strips are 80 μm wide and are isolated from the bottom by 50 μm thick Kapton layers, while the bottom strips are 350 μm wide. The width and the gap between top and bottom strips have been chosen to ensure an equal sharing of charge. The readout board is shown in the bottom right picture of Figure 3. The drift cathode and the readout board for the SBS BT GEM modules are also fabricated at the PCB workshop at CERN.

3. Module Construction Procedure

3.1. Support frame preparation

The support frames are first polished with sand-paper to remove any protruding glass fibers ends, and then cleaned in an ultrasonic bath filled with demineralized water for 15 minutes. The frames are then dried in air in the clean-room for 3 to 4 days. An electrical test of the frames is performed by placing them in between two metallic plates and applying a voltage of 4 kV between the plates. Finally, the parts of the frame exposed to the sensitive volume of the chamber are coated by applying, with a hand brush, a thin layer of polyurethane, Nuvovern LW + Hardener² to prevent surface irregularities, residual fiber ends or sharp edges.

3.2. High voltage test of the GEM foils

Each of the 24 high voltage (HV) sectors of a GEM foil is tested in the dry Nitrogen (N_2) box by applying a voltage $\Delta V = 550\text{V}$ across the foil through the sector top electrode and the bottom electrode and measuring the leakage current. The criterion for an acceptable foil is a current of less than 5 nA under HV for 2 min. During the assembly, the test is performed first on the bare foil and then on the framed foil. In both cases the foil is placed in the box with an open flow of N_2 (picture in top middle of Figure 3). When the chamber is completed, the test is repeated on each individual sector with N_2 gas flowing in the chamber. The distribution of the combined leakage current data from all 72 HV sectors of the foils used for the prototype is shown in Figure 4, with respectively from left to right, the measurement on the bare foils, on the framed foils and after the final assembly in the chamber. The mean value is well below the 5 nA/sector design goal.

² Polyurethane distributed by Walter Mäder AG, <http://www.maederlacke.ch>

Figure 4: Distribution of the leakage current over 72 HV sectors of the GEM foil before framing (left), after framing (middle) and inside the assembled chamber (right).

3.3. Stretching and gluing of the GEM foils

For the stretching of GEM foils, we use a custom-made mechanical stretcher, based on the original design by Alfonsi *et al.* [10], as shown in the picture on the top right of Figure 3. The base of the stretcher is a 0.5 inch thick aluminum template with alignment holes to match the holes in each of the support frames and GEM foils. The GEM foil is positioned and aligned on the aluminum template with dowel pins and clamped into the stretching jaws on all four sides. At two adjacent sides, the jaws are equipped with load cells connected to digital displays for monitoring the tension applied to the foil. A uniform tension of 0.5 kg/cm, corresponding to a pressure of 1 MPa, is applied along the foil. The spacer frame is glued onto the stretched foil using a resin epoxy (Araldite AY103 + HD991 Hardener)³. This glue is convenient for its excellent electrical behavior, well-studied aging and low outgassing properties. The framed foil is validated with a high voltage test of each sector as indicated above.

3.4. Final assembly

The base of the GEM module is formed by gluing the 2D readout onto the honeycomb support placed on an assembly support template and aligned with dowel pins. Then the three framed GEM foils, the framed cathode frame and the gas window are respectively glued onto the base. Finally, the gas connectors and tubes are mounted on the chamber to close it from the outside environment. Once these procedures are completed, the GEM module is removed from the clean room and a thin layer of Dow Corning 1-2577 RTV Coating⁴ is applied to all four sides to prevent further gas leaks. The 72 HV sectors of the 3 GEM foils in the chamber are once again tested by applying a voltage $\Delta V = 550$ V across the GEM foils with N_2 gas flowing inside the chamber before the HV board is mounted. Figure 5 shows a schematic and a picture of the HV board, with its main component, a custom-made ceramic

³ <http://commerce.sage.com/bag/upload/site/default/FT/Fran%C3%A7ais/Araldite/Araldite%20AY%20103-1%20+%20HY991.pdf>

⁴ <http://www.dowcorning.com/applications/search/default.aspx?R=263EN>

resistive divider available at CERN PCB workshop. The resistive divider consists of a resistor chain with 8 metallic contacts to distribute the voltage across the 6 GEM electrodes, the drift cathode and the ground from a single input HV power supply.

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148 Figure 5: (left) Schematic of the resistive divider with the voltage across the GEMs for HV = 4.1 kV on the HV
149 board; (right) HV board with the resistive divider and the protective resistors mounted on SBS BT GEM prototype

150 The HV board also hosts 10 MΩ protection resistors connected to each individual HV sector of GEM foils 1 and 2
151 and 1 MΩ resistors connected to the HV sectors of GEM foil 3. These resistors are used to limit the damage due to
152 discharge caused by a spark during the operation. Once the HV board is installed, a voltage scan, up to 4.2 kV
153 across the resistive divider, corresponding to an average voltage drop $\Delta V = 382$ V across a GEM foil, is performed
154 with N₂ flowing inside the detector. The chamber is kept at the high voltage 4.2 kV for about 24 hours to burn any
155 residual dust inside. Finally, after this last check, the module is filled with an Ar/CO₂ (70/30) gas mixture for tests
156 and characterization.

157 4. Performances of SBS BT GEM prototypes

158 Two 50 × 50 cm² SBS BT GEM prototypes were tested with cosmic and radioactive sources as well as in the high
159 energy hadron beam at the Fermilab Test Beam Facility (FTBF) in October 2013. The performance parameters of
160 the detectors such as the gain uniformity, efficiency and charge sharing of the readout board have been studied. The
161 chamber typically operates with an Ar/CO₂ (70/30) gas mixture for the tests with the applied high voltage in the
162 range of 4 kV to 4.2 kV on the resistive divider, corresponding to an average voltage ΔV range of 364 to 382 V
163 across the GEM foils. A front end (FE) electronic readout system, the Scalable Readout System (SRS) [11], based
164 on the APV25 readout chip and developed by the RD51 collaboration at CERN [12] was used to read out the SBS
165 BT GEM prototypes. The SRS was run with DATE [13] for the data acquisition and AMORE [13] for the

166 monitoring and data analysis. These two software packages have been developed by the ALICE experiment at
 167 CERN. A systematic pedestal run with the APV25 readout electronic connected to the detector is performed before
 168 the detector characterization with cosmics, radioactive source or test beam.

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 170 **Figure 6: (Left) Pedestal noise i.e. rms for each channels of one APV25 card connected to SBS BT GEM prototype;**
 171 **(right) Distribution of the pedestal rms for all 2560 APV25 channels (20 cards) connected to the prototype.**

172 During the pedestal run, the voltage ΔV across the GEM foils is set below 200 V to prevent cosmic particles from
 173 generating signals in the detector. The mean and the rms of the distribution of ADC (Analog-to-Digital Converter)
 174 counts representing respectively the pedestal offset and the pedestal noise is then compiled for every APV25
 175 channel and saved into a ROOT file. The left plot in Figure 6 shows the pedestal rms in ADC counts for each of the
 176 128 channels of one APV25 FE connected to the SBS BT GEM prototype. One ADC count is equal to
 177 approximately $232 e^-$ which is equivalent to 0.03712 fC. The rms varies from channel to channel with a minimum
 178 around 7 ADC counts and a maximum around 22 ADC counts. A similar pattern is seen for all the APV25 FE and
 179 is intrinsic to the internal routing of the channels inside the APV25 FE card. The total pedestal noise is a
 180 convolution between the intrinsic noise of the APV25 and the capacitance noise from the detector readout strip. The
 181 distribution of the pedestal rms for all 2560 APV25 channels connected to the SBS BT GEM prototype is shown in
 182 the right plot of Figure 6. This distribution shows two peaks at respectively, 9 and 12 ADC counts. These peaks
 183 correspond to the contributions to the pedestal noise due to the capacitance noise of the narrow top layer strips and
 184 the wide bottom layer strips of the prototype readout board as described in section 2.2.

185 For the characterization of the SBS BT GEM prototype, zero suppression is performed, after pedestal subtraction
 186 and common mode correction, by selecting only the strips above a certain threshold defined by $(n \times \sigma_{\text{strip}})$ with σ_{strip}
 187 being the rms of pedestal distribution for each strip described above in the example on the left plot of Figure 6.

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189 4.1.SBS BT GEM response and gain uniformity

190 A large set of cosmic data, with over 3×10^6 events from a weeklong run, was used to study the gain uniformity
 191 over the entire area of the chamber. The left plot in Figure 7 shows the 2D distribution of cluster position (x, y). A
 192 cluster is defined as a collection of consecutive strips with signals above zero suppression. The lack of events at the
 193 edges of the chamber is due to the limited size of the trigger scintillators used for the data acquisition.

194
 195 Figure 7: (left) 2D map of cluster position from cosmic data run; (right) 2D spatial distribution of average cluster
 196 charge (in ADC counts) with large cosmic data run: relative gain uniformity measurement.

197 The right plot in Figure 7 shows the 2D spatial uniformity of average gain (in ADC counts) of the SBS BT GEM
 198 prototype. The average gain as a function of position was calculated by filling in each bin of a 2D (x versus y)
 199 histogram with the total ADC values of all strips of the clusters with position coordinates falling into that bin over
 200 the entire run. At the end of the run, the ADC sum in each bin is divided by its count (the number of bin entries) to
 201 obtain the average ADC for that bin. The effect of the 300 μm wide spacers of the GEM frames is clearly shown
 202 here on the two plots and represents a dead area with an approximate width of 2 mm. The distinctive horizontal
 203 lines are due to additional efficiency drop caused by the HV sector boundaries on the GEM foils.

204 Left Figure 8 shows the cumulative strip occupancy of both x-plane and y-plane (1280 strips each) in the prototype
 205 from the same large cosmic data sample. The expected drops in the count distributions caused by the presence of
 206 the spacers in x-plane and y-plane as well as the HV sectors boundaries for y-plane are once again clearly shown.
 207 The wave-like structure seen on the two plots is the manifestation of the non-uniformity of the pedestal noise of the
 208 APV25 FE card described earlier in section 4, (see left plot in Figure 6). The periodicity of this pattern on the strip
 209 occupancy plots reflects the number of cards connected to the detector under test.

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Figure 8: Distribution of the hits from cosmic data across the 1280 strips in x (left) and y (right); drops in efficiency caused by the spacers and HV sectors boundaries are clearly visible.

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Figure 9: Distribution of average ADC counts per strip on the 1280 strips in x (left) and y (right) from cosmic data

The average gain (in ADC counts) per strip is shown in Figure 9. Each bin of the histograms represents the relative gain of the strip calculated using the same method as for the 2D relative gain uniformity map of Figure 7. The distribution shows good uniformity of the relative gain with less than 10 % variation in the x- direction and 15% in the y-direction. It should be noted that these results have been obtained without correcting non uniformities in the electronic response of the APV25 readout chip; this means that the effective gain variation of the detector could be even lower than what we observed.

4.2. Charge sharing of the 2D readout strips layer

The two SBS BT GEM prototypes were tested at FTBF in October 2013 as part of the slice sector test campaign by RD6-FLYSUB⁵ Consortium. The prototypes were installed on the FTBF MT6.2b stand in a setup that included 10 other GEM detectors with various sizes ranging from $10 \times 10 \text{ cm}^2$ small Triple-GEMs to 1 m long trapezoidal GEM. The first SBS BT GEM prototype was mounted on a moving table during the test beam. FTBF provides a 120 GeV primary proton beam as well as secondary hadron beam consisting in a mixture of kaons, pions, protons at energy ranging from 20 GeV to 32 GeV. The beam has a cycle of 1 min and 4 second spill of up to 2×10^4 particles. The facility also provided the external trigger for our readout electronics with the coincidence signal from 3 Photomultiplier Tube (PMT)-scintillators located upstream and downstream of our test beam setup. The performances of the prototypes were studied with the data taken during the test beam campaign. The left plot in Figure 10 shows data collected from a 32 GeV hadron beam at 24 different positions on the first SBS BT GEM prototype. Each spot on the plot represents the 2D profile of the beam with an approximate size of $8 \text{ cm} \times 2 \text{ cm}$ at one given location.

Figure 10: (Left) distribution of 32 GeV hadron beam reconstructed from 24 positions; (right) x vs. y charge sharing

The right plot in Figure 10 shows the charge sharing ratio equal to 1.33 between the x (top strips) and y (bottom strips) for this prototype. The non-equal sharing was caused by an issue related to the quality of the 2D readout boards used for the BT prototypes. Ideally, the Kapton material that insulates the top strips from the bottom strips

⁵ RD6-FLYSUB is a collaboration of researchers from Brookhaven National Laboratory, Florida Institute of Technology, Lawrence Livermore National Laboratory, Stony Brook University, University of Virginia, Weizmann Institute of Science and Yale University formed to carry out R&D for tracking and particle identification for detectors for a future electron-ion collider.

has a thickness of 50 μm and a width of 80 μm (which is same as width of the top strips). In reality, because of the chemical etching process during fabrication, the Kapton always displays a wedge-like shape with a larger width at its base than at the top, covering part of the exposed area of bottom strips. The left picture of Figure 11 shows a microscopic view of one of a readout board from the same batch as the ones used for the SBS prototypes. As the picture indicates, the Kapton layer is as wide as 160 μm (black arrows) at its base; this is twice the expected ideal width of 80 μm (white arrows). The excess Kapton material covers a portion of the bottom readout board reducing the total amount of charge collected by the bottom strips and therefore resulting in a non-equal charge sharing between the top and bottom strips.

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251 Figure 11: (Left) Poor quality readout board used for SBS BT GEM prototype module; (center) improved readout
 252 board quality used for SBS BT GEM production module; (right) equal charge sharing from a production module
 253 with improved quality.

254 Moreover, there is further degradation of charge sharing when the GEM detector is operated in a high rate
 255 environment due to the charging of the dielectric Kapton, which increases the shielding of the bottom strip layer.
 256 Since this issue was observed, the production procedures for SBS readout boards at the CERN PCB workshop were
 257 improved to ensure the required quality. Furthermore, a quality assurance process, using inspection with a high
 258 power microscope, was setup at the UVa detector lab to ensure that the Kapton width at the base is smaller than 100
 259 μm for all readout boards. The picture at the center of Figure 11 shows a new readout board of the required quality
 260 used for a newly built SBS BT GEM module; the plot on the right of Figure 11 shows the charge sharing ratio of
 261 approximately 1 obtained from the new module.

262 4.3. Efficiency and cluster size

263 The efficiency of the detector is defined as the number of events with at least one cluster in each of both readout
 264 layers (x-strips and y-strips) of the detector, divided by the number of triggered events. The left plot in Figure 12
 265 shows the efficiency curves for 3 different thresholds from a HV scan of the SBS BT GEM prototype. An
 266 efficiency plateau above 96% is reached at 4100 V, equivalent to an average voltage $\Delta V = 373\text{V}$ across the GEM

foils, for a $4 \times \sigma_{\text{strip}}$ threshold. The right plot in Figure 12 shows the cluster size, defined as the average number of the hits in the cluster, versus the average voltage ΔV across the GEM for the x and y planes of the prototype. The cluster size is smaller for the y-strips because of the same readout quality issue discussed in the previous paragraph. These results are consistent with what has been observed with similar GEM detectors before [7].

Figure 12: (Left) Efficiency vs. average voltage (ΔV) across the 3 GEM foils for various zero suppression thresholds; (right) Cluster size vs. ΔV across the 3 GEM foils of both x-and y-strips at $5 \times \sigma$ threshold.

4.4. Spatial resolution studies

The spatial resolution of the SBS prototype was also studied with FTBF test beam data. A detailed description of the setup and beam condition as well as the analysis and results will be published soon in a forthcoming paper and only a short summary of the resolution calculation is given here. The setup used during the FTBF test beam for the spatial resolution studies comprised of three small ($10 \times 10 \text{ cm}^2$) standard CERN Triple-GEMs used as trackers. Two of the small Triple-GEMs were located upstream of the SBS prototype with respect to the beam and the third one downstream. A simple least squared linear fit algorithm was used to fit the tracks. We used the geometric mean method described in [14] to calculate the spatial resolution in the x and y directions of the SBS BT GEM prototype. With this method, the resolution is obtained using the geometrical mean $\sigma = \sqrt{(\sigma_{\text{incl}} \times \sigma_{\text{excl}})}$ of the width of the track residual distribution of respectively inclusive and exclusive fitted tracks. For the inclusive fit, the data from both probed detectors (the SBS BT GEM prototype) and tracking detectors (small Triple-GEM trackers) are used to get the fitted track whereas in the case of the exclusive fit, only the data from the tracking detectors are used for the fitted track. The SBS BT GEM prototype has in principle the same characteristics as the small Triple-GEM trackers, and thus the FTBF setup provides the ideal configuration for an accurate estimation of the spatial resolution using the geometric mean method [14]. Figure 13 shows the inclusive and exclusive residuals for the x-

coordinate, with σ_x (excl.) $\approx 69 \mu\text{m}$ and σ_x (incl.) $\approx 51 \mu\text{m}$ respectively, and for y-coordinate, with σ_y (excl.) $\approx 77 \mu\text{m}$ and σ_y (incl.) $\approx 58 \mu\text{m}$ respectively, at the P1 location on the detector.

Figure 13 Track residual distribution from the exclusive (top) and inclusive methods (bottom) for x-coordinates (left) and y-coordinates (right) for the SBS BT GEM prototype.

Figure 14: (Left) 2D distribution of 120 GeV proton beam reconstructed from the eight positions scan during FTBF test beam; (right) spatial resolution for x-coordinates and y-coordinates at eight positions on SBS BT GEM prototype.

299 The beam spot positions on the SBS BT GEM prototype during the scan are shown on the left plot in Figure 14.
300 These values yield a measured resolution of $\sigma_x \approx 60 \mu\text{m}$ for x-strips and of $\sigma_y \approx 68 \mu\text{m}$ for y-strips at this location.
301 The right plot in Figure 14 shows the spatial resolution for x and y coordinates at eight different locations on the
302 detector. The resolution shows good uniformity across the detector with an average resolution of $59.53 \mu\text{m}$ for x-
303 strips and $62.88 \mu\text{m}$ for y-strips. The x-coordinate corresponds to the top readout layer, with narrower strips leading
304 to lower capacitance and lower noise while the y-coordinate corresponds to the bottom layer, with wider strips and
305 slightly higher capacitance and higher noise. Moreover, the bottom electrodes collect fewer charges than the top
306 strips because of the non-equal charge sharing discussed in paragraph 4.2. These two effects could explain the $5 \mu\text{m}$
307 difference between resolutions σ_x and σ_y . These resolutions are consistent with the expected performances for
308 standard Triple-GEM detectors. The slightly higher value of σ_y at the location P5 is explained by the presence of
309 $300 \mu\text{m}$ spacers at this location causing a local degradation of the spatial resolution.

310 5. Conclusion

311 A $50 \times 50 \text{ cm}^2$ GEM module was designed and prototyped at the University of Virginia for the Back Tracker GEM
312 chambers of the Super Bigbite Spectrometer at Jefferson lab. Two prototype modules were extensively tested using
313 cosmic, radioactive sources and test beam data. These data indicate that the detectors perform as expected meeting
314 the requirements of the Super Bigbite Spectrometer.

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322 References

- 323 [1] Thomas Jefferson National Accelerator Facility at < www.jlab.org >.
- 324 [2] The Super-Bigbite Spectrometer for Jefferson Lab Hall A
- 325 https://userweb.jlab.org/~mahbub/HallA/SBS/SBS-CDR_New.pdf
- 326 [3] F. Sauli, “*GEM: A new concept for electron amplification in gas detectors*”, Nucl. Instr. and Meth. A386, 531
- 327 (1997).
- 328 [http://dx.doi.org/10.1016/S0168-9002\(96\)01172-2](http://dx.doi.org/10.1016/S0168-9002(96)01172-2)
- 329 [4] B. Ketzer et al., “*Performance of triple GEM tracking detectors in the COMPASS experiment*”, Nucl. Instr.
- 330 and Meth. A 535 (2004) 314–318
- 331 <http://dx.doi.org/10.1016/j.nima.2004.07.146>
- 332 [5] C. Altunbas et al., “*Construction, Test and commissioning of the GEM tracking detector for compass*”, CERN-
- 333 EP/2002-008 and Nucl. Instr. and Meth. A 490, 177 (2002).
- 334 [http://dx.doi.org/10.1016/S0168-9002\(02\)00910-5](http://dx.doi.org/10.1016/S0168-9002(02)00910-5)
- 335 [6] B. Wojtsekhowski et al., “*Large Acceptance Proton Form Factor Ratio Measurements at 13 and 15 (GeV/c)²*
- 336 *Using Recoil Polarization Method*”, Jefferson Lab experiment E12-07-109 (2007).
- 337 http://www.jlab.org/exp_prog/proposals/07/PR12-07-109.pdf
- 338 [7] E. Basile, et al., “*Production status of the JLab Hall-A GEM and Si μ strip Tracker*”, Nucl. Instr. and Meth. A
- 339 (2012).
- 340 <http://dx.doi.org/10.1016/j.nima.2012.10.090>
- 341 [8] K. Gnanvo et al., “*Imaging of high-Z material for nuclear contraband detection with a minimal prototype of a*
- 342 *muon tomography station based on GEM detectors*”, Nucl. Instr. and Meth. A 652 (2011) 16–20
- 343 <http://dx.doi.org/10.1016/j.nima.2011.01.163>
- 344 [9] S. D. Pinto et al., “*Progress on large area GEMs*”, JINST 4 P12009 (2009)
- 345 <http://dx.doi.org/10.1088/1748-0221/4/12/P12009>
- 346 [10] M. Alfonsi et al., “*The LHCb Triple-GEM Detector for the Inner Region of the First Station of the Muon*
- 347 *System: Construction and Module-0 Performance*”, IEEE Trans. Nucl. Sci., vol. 53, Issue 1, pp.322-325,
- 348 (2006). <http://dx.doi.org/10.1109/NSSMIC.2004.1462057>
- 349 [11] S. Martoiu et al., “*Front End Electronics for the Scalable Readout System of RD51*”, in 2011 Proc. IEEE
- 350 Nucl. Sci. Symp., pp 2036-2038. <http://dx.doi.org/10.1109/NSSMIC.2011.6154414>
- 351 [12] RD51 Collaboration. <http://rd51-public.web.cern.ch/rd51-public/>
- 352 [13] DATE & AMORE: LHC ALICE Experiment DAQ & Monitoring Software,
- 353 <https://ph-dep-aid.web.cern.ch/ph-dep-aid/>
- 354 [14] T. Alexopoulos et al., “*Examining the Geometric Mean Method for the Extraction of Spatial Resolution*”,
- 355 JINST 9 P01003 (2014) <http://arxiv.org/abs/1311.2556>