EIC Proposal for R&D of Micromegas Detectors

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Abstract

Micromegas detectors are becoming increasingly popular for a variety of applications in nuclear and particle physics. They are thin, both physically and in terms of their material budget, perform well in high rate environments, and the assembly and operation is relatively simple. The readout design is flexible and can be easily adapted to the experimental needs whether that requires one or two dimensional hit positioning to better than 100 μm or pad/pixel readout with fine granularity to sample particle flow. We propose to develop the technology and expertise to produce micromegas detectors at the MIT-Bates research and engineering facility. Having this capability locally will enable us to study the production and operation of micromegas detectors with various configurations and modifications. We would welcome other individuals and institutes to participate in this and believe this will provide the capability and experience to design, innovate, and produce this detector technology for EIC detectors and other, future experiments or applications.

1 Introduction

Instrumentation utilizing gas amplification of electrons in a high electric field ($\sim 40,000$ V/cm) has revolutionised nuclear and particle physics detectors and experiments since G. Charpak first introduced the MWPC in 1968 [1]. Since then there has been a steady development of new detectors based on this principle (drift chambers, time projection chambers, *etc.*).

However, limitations arise with wire based designs in terms of mechanical constraints, granularity, rate capability, ion back-flow, *etc.* Advances in photolithography permitted the fine wires to be replaced by fine lines on printed circuit boards (PCBs) and micro-strip gas chambers were developed by A. Oed in 1988 [2] capable of high rates and with reduced ion back-flow.

Further development of PCB based approaches followed with the micro-mesh gas structure (micromegas) by Y. Giomataris at CEA-Saclay in 1996 [3] and then the gas electron multipler (GEM) by F. Sauli at CERN also in 1996. [4]. Both of these technologies have been advanced by the international collaboration RD51 [5] based at CERN and continuing R&D efforts at CERN, CEA-Saclay, and elsewhere. While some parts of the technology for both GEM and micromegas production have been passed on to industrial partners; the design and innovation process remains at the physics laboratories. Also the careful assembly of the detectors for nuclear and particle physics experiments requires the experience and skilled technical expertise at the physics laboratories.

The research and engineering facility at MIT-Bates already has extensive experience in designing and producing GEM detectors. We now propose to develop, in collaboration with our colleagues at CERN and CEA-Saclay, the capability and expertise to also produce micromegas detectors. We believe such a facility will have a number of benefits and serve as a valuable resource for future EIC [6] detector development. We welcome other individuals and institutions to also participate and use this facility. The benefits we envision include:

- expertise and experience in producing both GEM and micromegas detectors that will facilitate the detailed design of future detectors,
- leveraging the existing facilities at MIT-Bates (mechanical and electronic engineering, experienced technicians, clean room facilities, equipment, *etc.*),
- producing the micromegas structures in house (readout PCBs would be produced commercially) and assembling complete detectors that can be integrated and tested with readout electronics before transport to the experiment, and
- production of large area (up to 0.5×2.05 m^2) detectors as maybe required for the EIC or other experiments.

The following section will describe briefly the basic concept and fabrication of micromegas detectors. It will also outline some of the new improvements or innovations we would investigate and improve upon over the lifetime of this project. The next section will present the facility we propose to develop at MIT-Bates and how

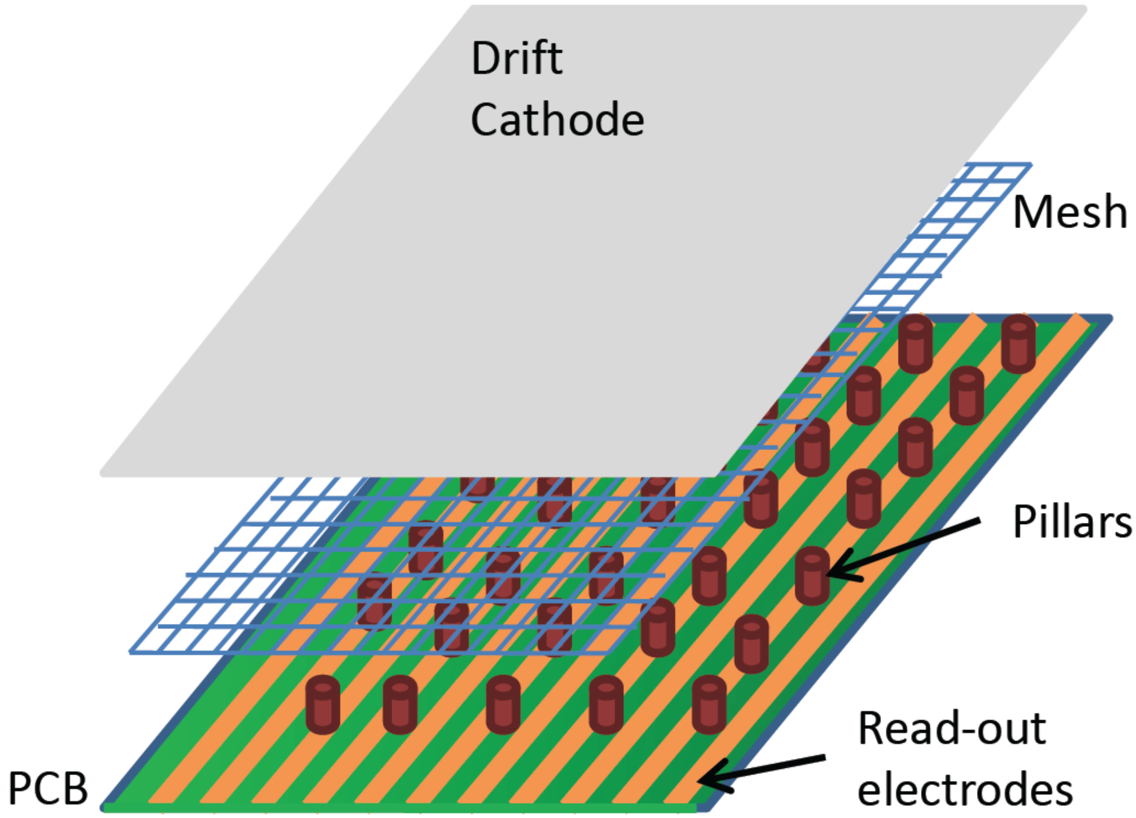

Figure 1: Basic concept behind a micromegas detector.

it leverages existing facilities and experience. Then there will be a section outlining the costs involved for which we are requesting support.

2 Micromegas

2.1 Basic concept

Micromegas, or micro mesh gas structure, detectors were originally proposed by Y. Giomataris at CEA-Saclay in 1996 [3]. The basic concept is illustrated in Fig. 1. The drift cathode is held at ≈ -600 V depending on the gap (usually 3–5 mm) to the wire mesh. The mesh is held at ≈ -400 V depending on the gap (usually ~ 130 μm) to the readout PCB (anode) at ground potential. The mesh is fixed by the insulating pillars that are also fixed to the PCB. The entire assembly is contained inside a gas

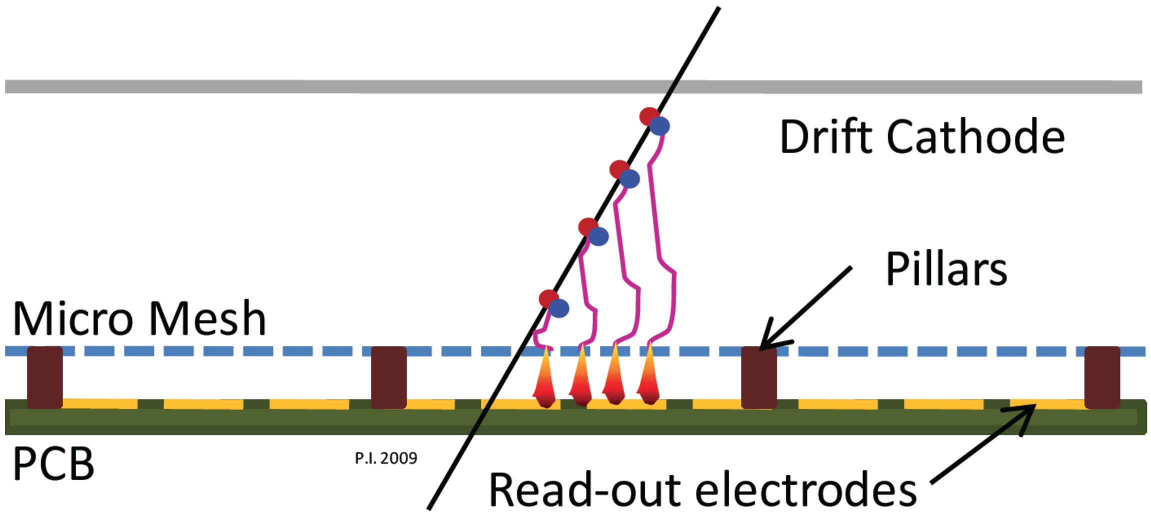

Figure 2

volume (*e.g.* Ar:CO2 90:10) typically at atmospheric pressure.

The micromegas detector operation is shown in Fig. 2. When a charged particle passes through the drift region it ionises the gas and the electrons drift towards the wire mesh. The mesh is highly transparent to the drifting electrons and most pass through where the drift field is now $\approx 40,000$ V/cm and the electrons begin to cascade. The resulting shower is collected on the readout strips and the centroid of the strips collecting charge provides information on the position or the initial charged particle.

Micromegas detectors offer many advantages:

- physically thin, 3–5 mm,
- materially thin, $\sim 0.5\%$ X_0,
- can be curved to form cylindrical detectors,
- the PCB readout can be adapted simply as needed (simple strips for 1D tracking or lines and pads for 2D readout, stereo, XUV for better hit matching, or pads/pixels)
- can operate in a high rate environment,
- because the mesh is so close the ion back-flow is fast, and

- assembly is much simpler than similar detectors.

Since the original concept was presented, considerable developments have been introduced and this detector technology has been used or is being proposed for numerous physics experiments, for example:

- the COMPASS experiment,[7–10]
- the CAST solar axion search,[11,12]
- the MIMAC dark matter search,[13]
- the CMS and ATLAS upgrades,[14]
- sampling calorimetry[15] for a future ILC, and
- neutron detection in ADS projects.[16]

2.2 Fabrication

The fabrication process is primarily concerned with the production of what is referred to as the "bulk" material. The various steps are outlined in Fig. 3. First, the readout PCB with the desired readout geometry is produced (generally purchased from a commercial manufacturer). Over this is laminated a layer of photoresist or, in this case, Vacrel, a solder-stop mask. Then the wire mesh is stretched flat over the first layer of photoresist and a second layer of photoresist is laminated over the wire mesh encapsulating the wire mesh. The next steps (not shown) involve the lithography process where a photomask with a rectangular array of circular "holes" typically 400 μm in diameter with 2–4 mm spacing in both the X and Y directions is placed over the photoresist and exposed to UV light. The photoresist is of negative tone, which means where exposed to UV-light the photoresist is polymerised and hardens. The next step is to develop the assembly where the unexposed photoresist is stripped away leaving the posts supporting the wire mesh. This becomes the "bulk" material for the micromegas.

The "bulk" process has been transfered to industry in France and Italy. In this proposal we are proposing to perform the "bulk" process at MIT-Bates similar to what is done at CEA-Saclay and CERN. We consider this a necessary step in gaining the necessary experience and expertise that will allow us to successfully design, innovate, and produce detectors in the future.

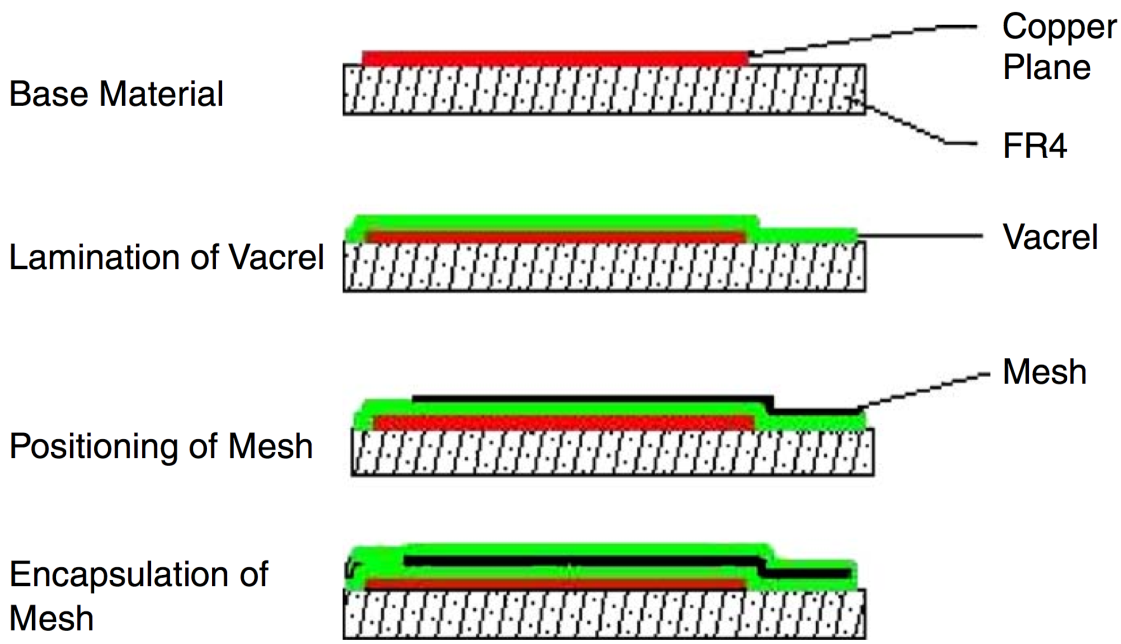

Figure 3: The fabrication steps as described by Y. Giomataris.[17]

2.3 Innovations

A number of improvements have already been made to micromegas. Some of these will be briefly described in the following. With a micromegas facility at MIT-Bates we intend to test and study these and other innovations with the intention of improving their implementation to optimise performance and production. As we gain experience with micromegas production and operation we expect to be able to make new innovations of our own.

2.3.1 Readout PCB patterns

As already mentioned, micromegas offer a number of desirable features when designing detectors for nuclear and particle physics experiments. One is the flexibility of the readout PCB that can be tailored to the needs of the experiment. The readout PCB patterns described below are also commonly used with GEM detectors; so we are already familiar with their design and production.

In the sections above a simple, strip pattern on the readout PCB was used for the illustrations. This of course provides hit position measurements in one dimension. The resolution depends on the pitch and width of the lines but resolutions on the

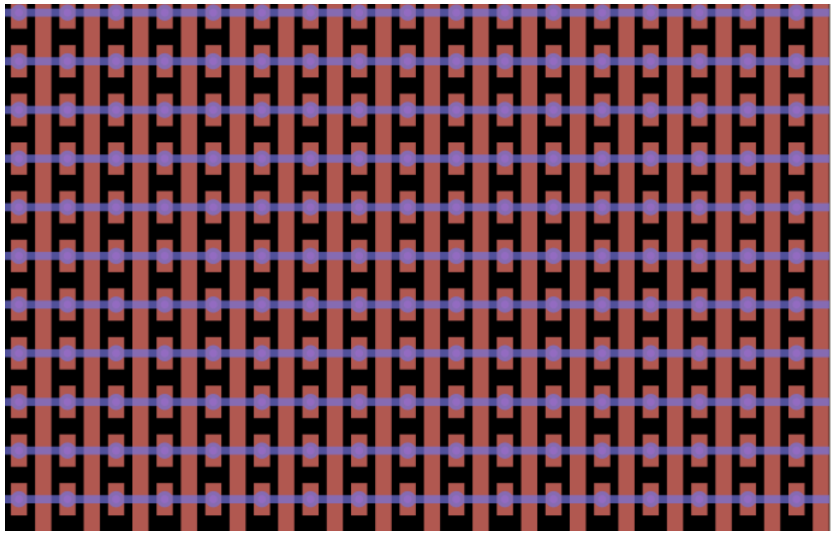

Figure 4: Example of a 2D readout PCB pattern. Copper coloured lines and pad represent the actual copper on the top surface of the PCB. These lines provide a measure of position in the horizontal dimension. The blue dots and lines represent the vias connecting the pads to copper lines running on the underside of the PCB. Thus the pads are connected horizontally and measure the vertical position.

order of 50 μm are possible.

Using a readout PCB with a line and pad design as shown in Fig. 4 a two dimensional hit position can be determined with resolutions on the order of 80 μm with the appropriate choice line and pad width and pitch. Depending on the position resolutions needed by the experiment the PCB pattern can be tailored separately in X and Y directions as desired.

Other patterns, like Fig. 5, offer another way to tailor the resolution separately in the two dimensions in a manner similar to the stereo pattern of wires in some drift chamber tracking detectors. In the example shown the horizontal resolution is related to the length of pads while the vertical resolution is related to the smaller pitch between the lines.

Both of the 2D patterns described above have a problem when more than one track crosses the detector within the same time window. With a single track there is a unique X and Y read out. But with two tracks there are four combinations of $X_{1,2}$ and $Y_{1,2}$. To resolve the ghost combinations, it is necessary to look at the charge associated with each hit and match the correct pair. This requires knowing the charge-sharing ratio between X and Y readout.

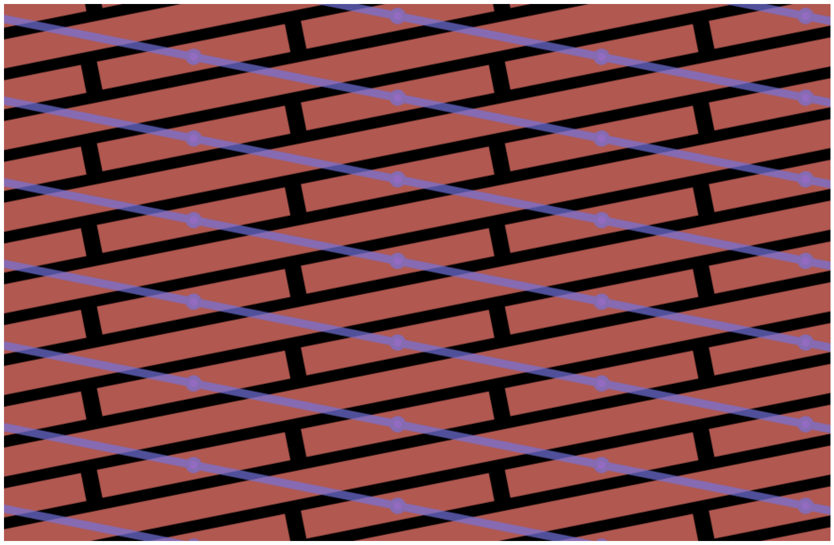

Figure 5: 2D readout PCB pattern with a stereo pattern.

One way to resolve the hit ambiguity when more than one track crosses the detector is to use an XUV pattern shown in Fig. 6. However, this design requires a three layer PCB.

2.3.2 Resistive anode layers

Like GEM detectors, micromegas can experience sparking or electrical breakdown when a highly ionising particle passes through the detector. To counter this it is possible to apply a thin insulating layer over the readout PCB with resistive lines, on the top side, parallel to the the readout lines. The posts and wire mesh are then built on top of this layer. This concept is illustrated in Figs. 7 and 8 taken from the paper by Burnens[18] though others have used a similar technique. With this approach discharges are quickly stopped because the resistive lines rise to the potential of the mesh reducing the potential difference locally below the discharge voltage. This also protects the readout electronics connected as normal to the readout lines as they are now capacitively coupled to the resistive lines that collect the charge. Another advantage with this resistive layer design is that the mesh can be run at a higher voltage resulting in a higher gain.

Various techniques for producing the resistive layer have been used. We would investigate this further to optimise the production. Perhaps this can be combined with the readout PCB by the commercial manufacturer.

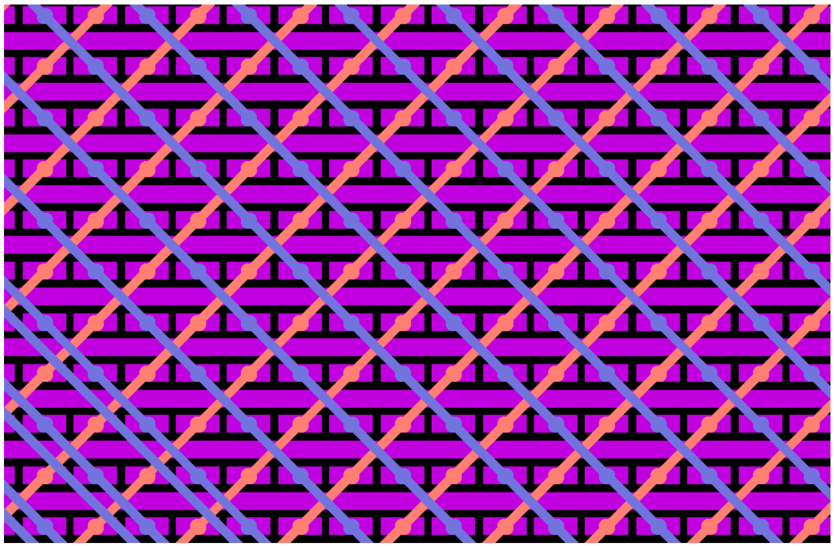

Figure 6: 2D readout PCB pattern with an XUV pattern.

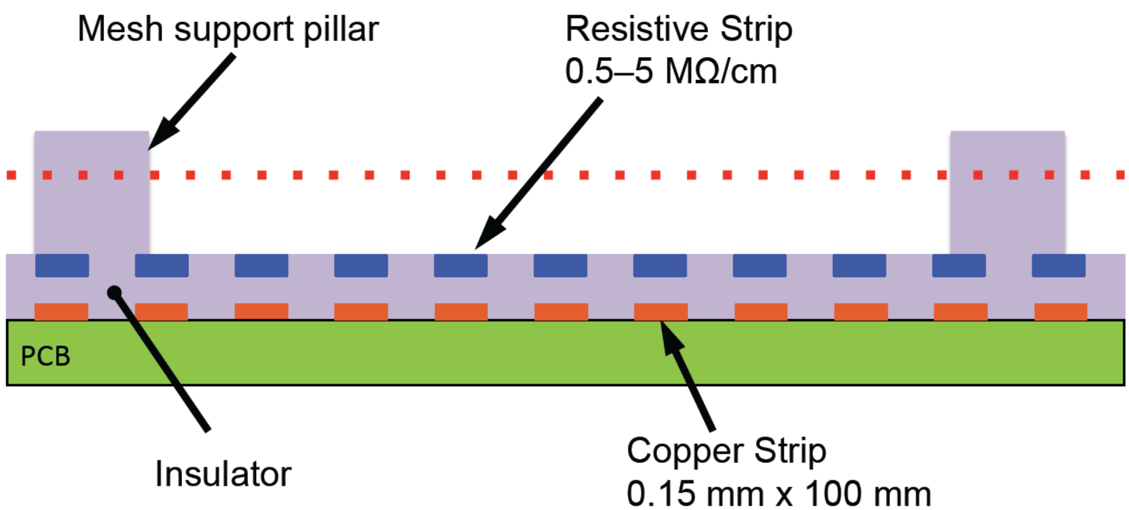

Figure 7: End view of a micromegas "bulk" construction with resistive lines applied over the readout PCB lines before building the posts and mesh.

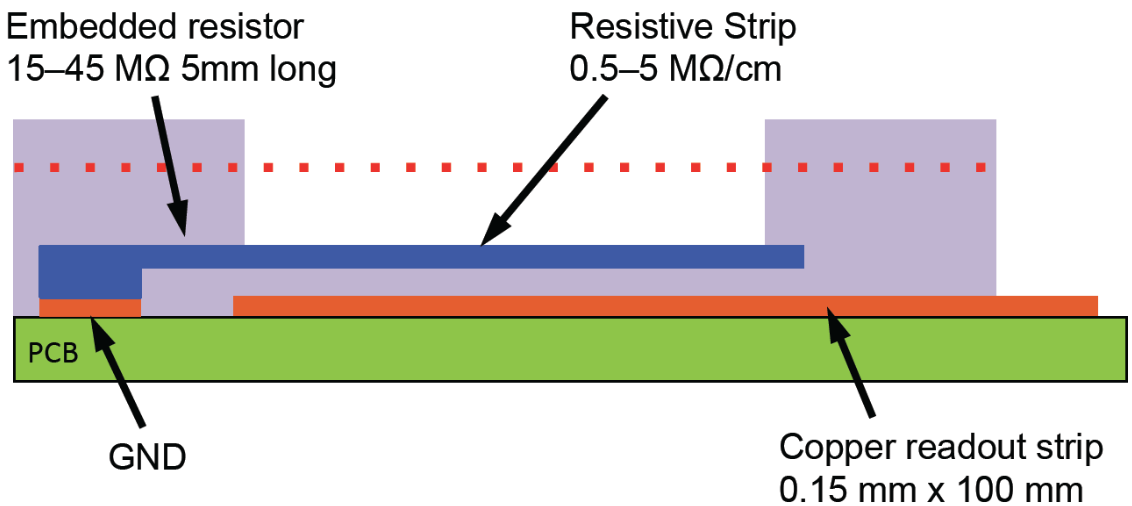

Figure 8: Side view of a micromegas "bulk" construction with resistive lines applied over the readout PCB lines before building the posts and mesh.

The resistive layer, however, makes 2D readout more difficult. If a normal 2D pattern of lines and pads is used on the readout PCB and the resistive lines are run above readout lines, the resistive lines capacitively couple to all the rows of pads. This may not be a serious limitation according to a study by M. Byszewski and J. Wotschack[19] illustrated in Fig. 9. In this scheme the readout PCB has X lines on the underside of the PCB and Y lines on the top side. The resistive lines run parallel to the X lines. The signal on the X lines is as expected and can be used as normal. Not surprisingly several lines in the Y direction have signals but the centroid reproduces well the known track position with good resolution. This technique has also been successfully applied using an XUV pattern.

2.3.3 Alternate assembly schemes

Production of micromegas detectors are in many ways simpler than other tracking detectors. First, the "bulk" assembly is prepared and can be inspected, cleaned, and tested by itself before enclosing it in a gas volume and adding the drift HV layer. Any problems can be addressed and possibly fixed before sealing the detector.

Testing the "bulk" assembly is similar to testing individual GEM foils. However, after starting the assemble of a GEM detector problems with the first GEM foil or readout board are difficult to fix after installing the second or third GEM foil or the drift HV layer (often glued together). With a micromegas detector the "bulk"

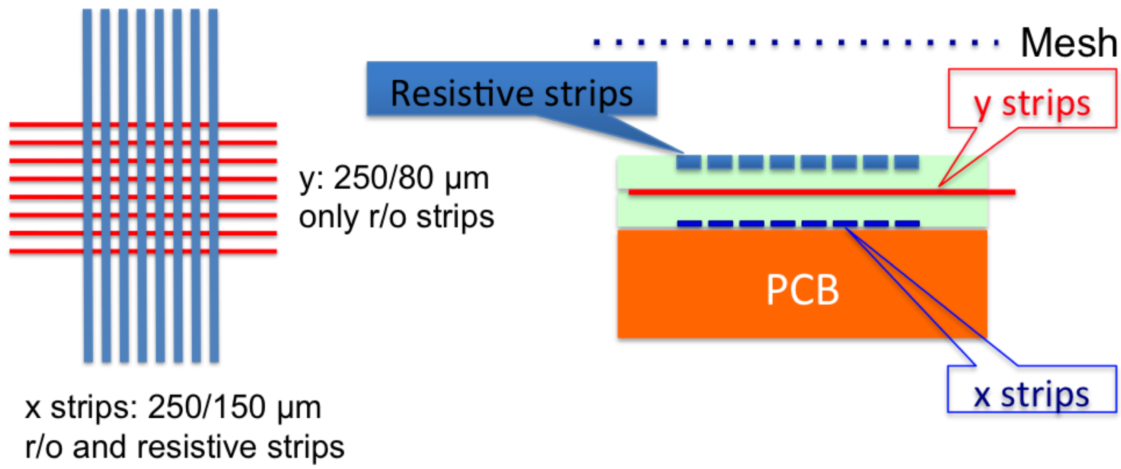

Figure 9: 2D readout scheme using resistive lines above a two layer, 2D readout pattern.[19]

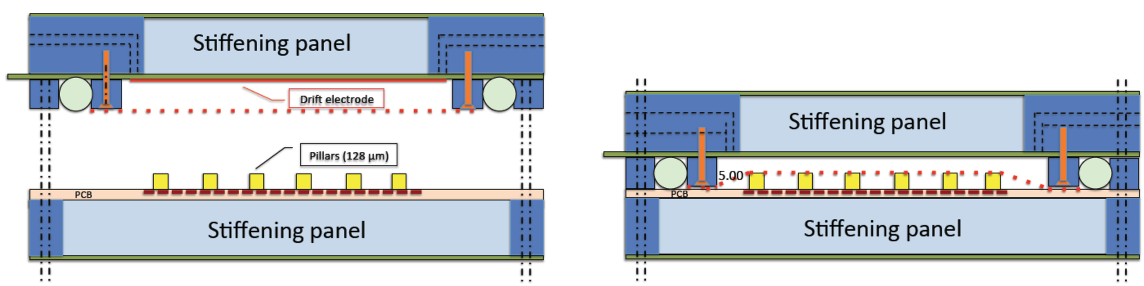

Figure 10: Proposed assembly approach for the ATLAS micromegas upgrade.

assembly can be tested and fixed as necessary and then there is effectively a single step to complete the detector *i.e.* attach the drift HV layer.

On the other hand, sandwiching the wire mesh in the photoresist is a complicated step. With its proposed upgrade, the ATLAS collaboration is planning to remove the wire mesh from the "bulk" assembly and rather include it as part of the drift volume. This is illustrated schematically in Fig. 10. The wire mesh is stretched and fixed to the top half of the detector frame while the bottom half holds the readout PCB and the posts of photoresist. When assembled the wire mesh is stretched over the posts as desired. This design also has the advantage that it can be taken apart and repaired, cleaned, or replaced as needed. However, it does require substantial frames that will be dead areas in the detector so may only be practical for large area micromegas detectors.

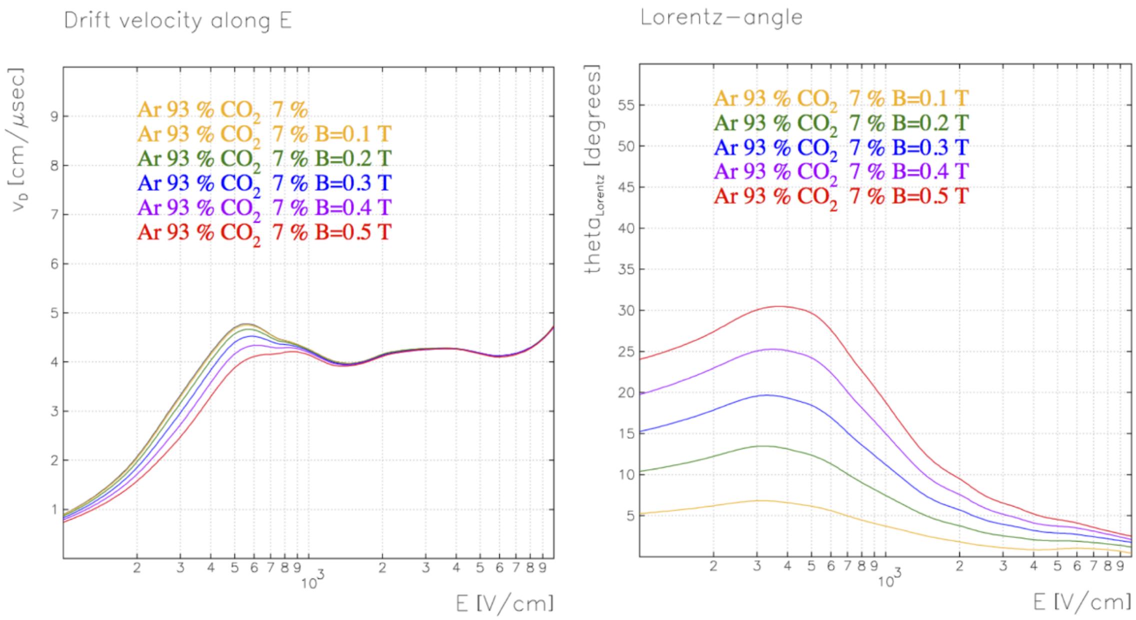

Figure 11: Drift speed and Lorentz angle for Ar:CO_2 93:7 as a function of the drift electric field and applied, perpendicular magnetic field.

2.3.4 Micromegas in magnetic fields

One consideration in designing a tracking detector is the interaction between any applied magnetic field and the drifting electrons that are detected to yield the particle trajectory. In micromegas the drift distance is short, 3–5 mm typically so the effect is small and the gas mixture and drift field can always be chosen to minimise the magnetic field's impact keeping in mind other considerations like intrinsic resolution, see Fig. 11.

The track reconstruction can account for the Lorentz angle and adjust the track position accordingly so long as the gas mixture and magnetic field are know. This is illustrated in Fig. 12. Components of the magnetic field parallel to the drift field do not apply. Components perpendicular to the drift field produce a Lorentz force causing the electron drift to deviate from the expected, direct line but in a predictable manner.

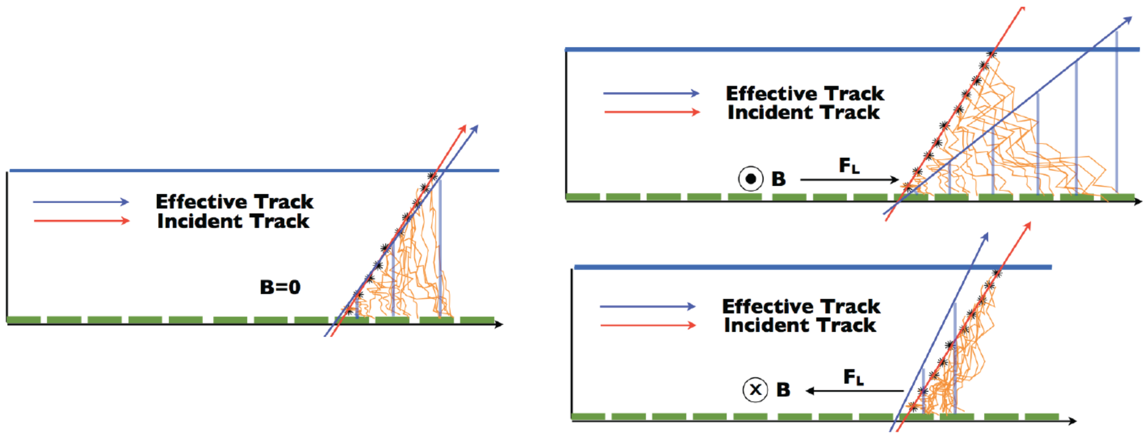

Figure 12: Effect on reconstructed track position for different directions of an applied magnetic field perpendicular to the drift field.

3 Micromegas production facility at MIT-Bates

We are proposing to develop a micromegas production facility at MIT-Bates. The purpose is to gain experience and expertise in the construction and operation of micromegas detectors that will be used in future experiments. Having a local expertise will facilitate the design and innovation of future detectors and benefit the community. Other individuals and institutions are also welcome to participate in this effort.

We leverage the existing facilities at MIT-Bates in terms of the mechanical and electrical engineering resources, experience building and developing other types of detector including GEMs, clean rooms, *etc.*

When we produced GEM detectors for STAR, OLYMPUS, and other experiments we also developed close ties with the high-tech, PCB manufacturing firm Tech-Etch[1] just south of Boston, and worked with them to produce the necessary, high quality readout PCBs and GEM foils that were built into the various GEM detectors. We understand that Tech-Etch is upgrading their facilities to produce large area PCBs. This, together with the facility we are proposing for MIT-Bates, would enable us to produce large area micromegas.

In addition, as members of the RD51 collaboration and together with our colleagues at CEA-Saclay, we can work together to improve micromegas detector production and performance. To facilitate this we propose to send two of our engineers,

[1]Tech-Etch, 45 Aldrin Road, Plymouth, MA 02360 USA

one electrical and the one mechanical, to CERN and Saclay to see first hand the facilities there and to study the process. In addition we would like to send one of the MIT post-doctoral physicists to Saclay for an extended time to work there building micromegas detectors so he can learn all the details and points requiring special care during the production. The details for this are not finalised at this time.

3.1 The micromegas laboratory at MIT-Bates

Effectively we wish to develop a facility similar to the facility at Saclay and CERN for producing micromegas.

We do not intend to produce the readout PCBs as these are complicated products requiring copper etching, copper deposition, laser drilling of vias, *etc.* that would be very expensive to reproduce and not economical. Therefore we will buy the readout PCBs from a company like Tech-Etch with whom we have a good relationship and who has produced similar PCBs for our GEM projects. We will of course design the readout PCBs ourselves to meet the specific needs of the detector.

The facility we are proposing to develop at MIT-Bates would allow us to laminate the photoresist, sandwich the wire mesh, and expose and develope the posts that support the wire mesh. In controlling these steps we will learn the details of the production and be able to optimise the different steps.

We could also investigate different schemes for appling the resistive layer. For example ink-jet printing of resistive lines to a Kapton foil that would be laminated over the readout PCB. Or perhaps the resistive layer could be produced together with the PCB by Tech-Etch.

With the alternative assembly technique discussed above for the ATLAS upgrade, where the wire mesh is part of the drift volume "half" of the detector; it may be possible and economical to transfer the entire production of readout PCB, with the resistive layer, and building the support posts, to a company like Tech-Etch. However, for now, we feel there is so much scope for development and optimisation that it is best done in house where we can change the design from one day to the next and experiment with new ideas.

To this end we request funding to purchase the following major items of equipment:

- hot roll laminator,

- UV exposure system,

- spray developer line, and

Figure 13: A hot roll laminator.

- room and infrastructure items.

Each of the above items will be discussed briefly below.

We also request support for the engineers and technicians who will work together with the physicists producing this facility and also in designing and studying micromegas detector built at MIT-Bates.

3.1.1 Hot roll laminator

This is a standard piece of equipment and not feasible or economical to build ourselves. It needs to be wide enough to accept the widest PCB we expect to handle (24 inches is a standard size). A typical unit we have identified is shown in Fig. 13.

3.1.2 Exposure unit

After the photoresist with the encapsulated wire mesh has been laminated to the readout PCB the pattern of posts must be produced by the lithographic process. A standard approach to this is to produce a photomask that is transparent where you want the posts and opaque everywhere else. This is aligned over the PCB and photoresist combination and then held in close contact by covering it with a clear

Figure 14: Conveyor style UV exposure unit.

mylar foil in a frame and pulling a vacuum on the volume. This assembly is then passed under a UV light source to deliver a know intensity of light to the photoresist.

A unit that we could develop for our purposes is shown in Fig. 14. We would need to make a suitable vacuum frame but this would not be too difficult. This approach, as opposed to more common "drawer" exposure units, has the advantage that we are not constrained by the length and only constrained in the width. Thus we can produce detectors in a wide range of sizes.

An alternative approach for exposing the photoresist through a photomask is to use laser direct imaging, LDI. This does not use photomasks but rather rasters a tightly collimated beam of laser light over the surface of the photoresist with a shutter opening and closing to produce the desired effect. Note the PCB/photoresist lamination still needs a vacuum chuck to hold it flat during the bed motion. Commercial LDI machines start at $700,000 and are designed for high volume production with a powerful laser divided into a hundred separate beams controlled by rotating mirrors and lens systems. They produce feature sizes less than 25 μm with similar gaps. Also they are mostly limited to standard size PCB panels (24×24 inches^2).

The pattern of posts in micromegas are typically rectangular arrays 2–4 mm on a side and the posts themselves are 300-400 μm in diameter. Such a simple pattern suggests a simple LDI machine could be developed. For example, commercial systems as shown in Fig. 15 with a laser diode Fig. 16 are available with software control packages compatible with standard Gerber or DXF CAD files. The system shown

Figure 15: Commercial R&D laboratory laser direct imaging system.

has a resolution of 50 μm, more than sufficient for our needs.

The system shown in Fig. 15 is of course too small for our plans but it serves as an existence proof of a possible approach we could take at MIT-Bates. We could use a similar laser diode system or a laser/mirror combination with a large XY table and drive control system specifically for micromegas.

Laser direct imaging has a number of advantages over photomask operations that make this approach interesting to consider for this proposal. Some of the advantages are:

- no need for photomasks that are either purchased commercially or require an expensive photoplotter,
- changes in an LDI program is as fast as a CAD system can produce a new file
- photomasks need to be stored and handled carefully to avoid defects that are propagated to the final product,
- production runs usually require expensive silver or chrome plated, glass photomasks,

Figure 16: Commercial R&D laboratory laser diode.

Another interesting attachment available for the XY system shown above is a dispensing unit Fig. 17. This would be a potential means of applying a resistive line. Similarly there are optical inspection and alignment, drilling and routing attachments with automated tool exchange that might be useful.

The dispensing unit might also be capable of producing a uniform drop of epoxy or similar substance that could perform as the posts and thus eliminate the need for the lamination, exposure, and developing steps in micromegas. Or possibly a 3D printing technique could be similarly used. With our own facility at MIT-Bates we could investigate such ideas.

3.1.3 Spray developer station

To develop the exposed photoresist, stripping the unexposed resist leaving the posts requires a developer station Fig. 18. This consists of rows of sprays operating on the boards as they pass beneath on a conveyor system. There are typically six stages to such a system: load, developer, stop bath, clean rinse, dry, and unload. Such system are not complicated but are also not too expensive and possibly simpler systems are also available with more research.

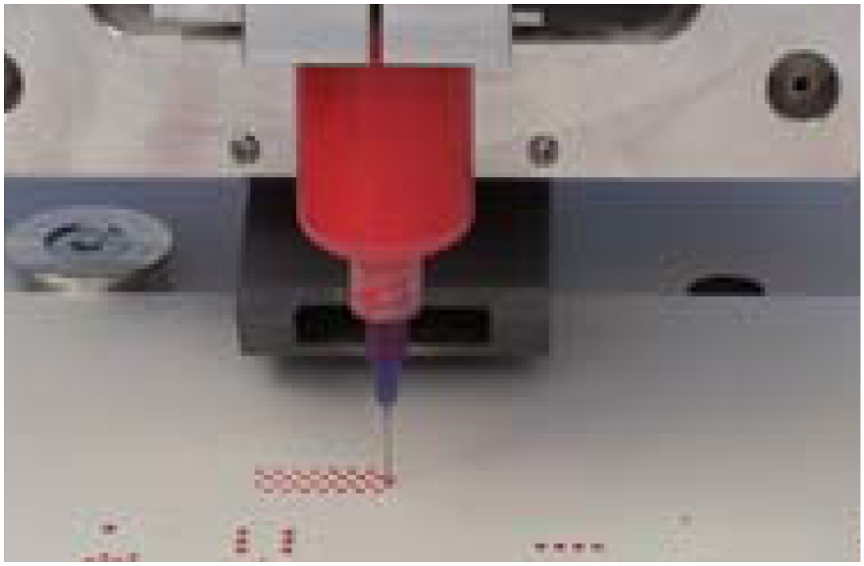

Figure 17: Dispensing unit.

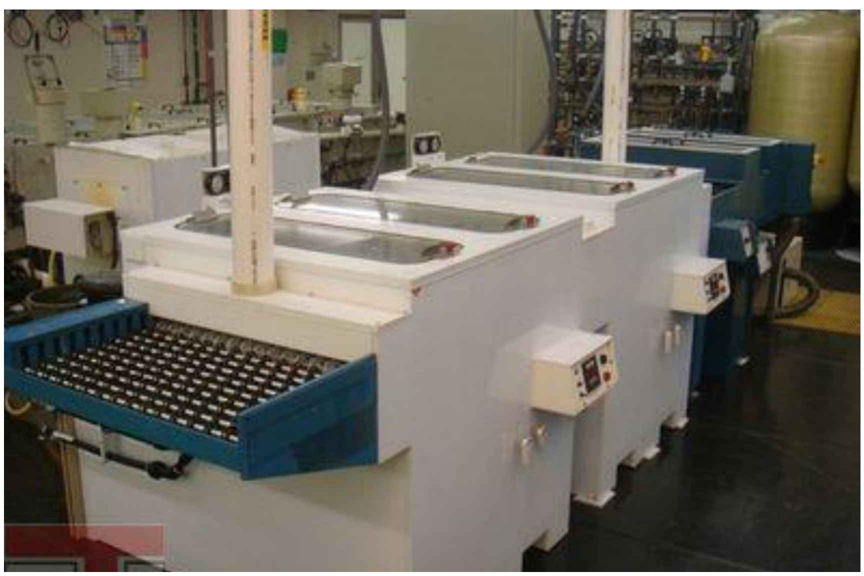

Figure 18: Spray developer station.

3.1.4 Room and infrastructure

We propose to assembly a room in one of the former RF bays at MIT-Bates close to the existing clean room. The new room would be made from prefabricated wall, floors, and ceiling panels. It would need a double door system and yellow lights to avoid accidentally exposing the photoresist. In addition to the equipment and requisite power and water we will also require work surfaces, chairs, storage, and filtered, positive ventilation.

3.2 Detector assembly and testing

After the "bulk" micromegas are produced in the new facility they can be transfered to the existing clean room. There the "bulk" can be tested and, if successful, fitted with the enclosing gas volume and drift foil to form a complete detector. This can be tested for gas tightness and with HV.

To further test and study the performance as a detector we have numerous scintillators with PMTs and GEM tracking detectors to form a cosmic ray test stand. Radioactive sources could also be used.

To readout the detectors we have two options. We can use the existing APV chips and readout system purchased and developed for the OLYMPUS experiment. Or perhaps we could purchase or borrow one of the DREAM chip boards being developed at CEA-Saclay. Other hardware like scopes, power supplies, *etc.* are readily available at MIT-Bates

4 Budget request

The following tables outline the funding we are requesting for this project for the three fiscal years 2015–2017.

Table 1 lists the major equipment items as described above. Most of these items are exempt from the overhead at MIT but some items like the purchased readout PCBs, photoresist, chemicals, and other consumables have overhead included in the cost shown.

As was discussed above we would like to send two engineers (Ben Buck and Jason Bessuille) to CERN and CEA-Saclay to observe and learn the production process from these two existing facilities. In addition it would be very useful for one of the post-doctoral physicists (Dr. Ross Corliss) to spend an extended time at Saclay to gain experience in the whole process and learn where the difficult steps are and what details need to be cared for. This is best learnt by actually building several micromegas detectors. This still needs to be finalised with Saclay. The cost, including overhead, for this travel is given in Table 2.

The engineers and technicians at MIT-Bates are salaried and need to be paid from the projects they are assigned. The costs for this, including overhead, is given in Table 3

Finally, the total request is given in Table 4.

Please note that all these costs represent our best estimates of the final costs. No contingency has been applied.

Table 1: Equipment and consumables budget including overhead

Item	2015	2016	2017
Laminator	10.0 k$		
Exposure unit	70.0 k$		
Developer station	40.0 k$		
Room, infrastructure	50.0 k$		
PCB, Consumables	73.1 k$	91.4 k$	109.7 k$
Total	243.1 k$	91.4 k$	109.7 k$

Table 2: Travel budget including overhead.

Item	2015	2016	2017
2 Engineers, 1 week Saclay + 1 week CERN	21.9 k$		
Post-doc, 3×2 months, Saclay	54.9 k$	27.4 k$	
Total	76.8 k$	27.4 k$	

Table 3: Manpower budget including overhead.

Item	2015	2016	2017
Engineer	0.4 FTE	0.2 FTE	0.2 FTE
	77.2 k$	39.8 k$	41.0 k$
Technician	0.25 FTE	0.25 FTE	0.25 FTE
	48.8 k$	50.3 k$	51.8 k$
Total	126.0 k$	90.1 k$	92.8 k$

Table 4: Total yearly budget request including overhead.

Item	2015	2016	2017
Total	445.9 k$	208.9 k$	201.5 k$

5 Summary

Micromegas detectors will be an important detector technology at EIC and in the future. In order to optimise the design, production, and implementation of this technology it will be important to have first hand experience in their production and operation. To this end we propose to develop the capability at the research and engineering facility at MIT-Bates to produce micromegas detectors and request funding to support this effort. We would welcome participation from individuals or other institutes to join us to improve and apply this technology for the future.

References

[1] Georges Charpak, R Bouclier, T Bressani, J Favier, and C Zupancic. The use of multiwire proportional counters to select and localize charged particles. *Nucl.Instrum.Meth.*, 62:262–268, 1968.

[2] A. Oed. Position Sensitive Detector with Microstrip Anode for electron Multiplication with Gases. *Nucl.Instrum.Meth.*, A263:351–359, 1988. doi: 10.1016/0168-9002(88)90970-9.

[3] Y Giomataris, P Rebourgeard, J P Robert, and Georges Charpak. MICROMEGAS: A High granularity position sensitive gaseous detector for high particle flux environments. *Nucl.Instrum.Meth.*, A376:29–35, 1996.

[4] F Sauli. GEM: A new concept for electron amplification in gas detectors. *Nucl.Instrum.Meth.*, A386:531–534, 1997.

[5] RD51 Collaboration Welcome. URL `http://rd51-public.web.cern.ch/rd51-public/Welcome.`

[6] A Accardi, J L Albacete, M Anselmino, N Armesto, E C Aschenauer, A Bacchetta, D Boer, W Brooks, T Burton, N B Chang, W T Deng, A Deshpande, M Diehl, A Dumitru, R Dupre, R Ent, S Fazio, H Gao, V Guzey, H Hakobyan, Y Hao, D Hasch, R Holt, T Horn, M Huang, A Hutton, C Hyde, J Jalilian-Marian, S Klein, B Kopeliovich, Y Kovchegov, K Kumar, M A C Lamont, T Lappi, J H Lee, Y Lee, E M Levin, F L Lin, V Litvinenko, T W Ludlam, C Marquet, Z E Meziani, R McKeown, A Metz, R Milner, V S Morozov, A H Mueller, B Müller, D Müller, P Nadel-Turonski, A Prokudin, V Ptitsyn, X Qian, J W Qiu, M Ramsey-Musolf, T Roser, F Sabatié, R Sassot, G Schnell, P Schweitzer, E Sichtermann, M Stratmann, M Strikman, M Sullivan, S Taneja,

T Toll, D Trbojevic, T Ullrich, R Venugopalan, S Vigdor, W Vogelsang, C Weiss, B W Xiao, F Yuan, Y H Zhang, and L Zheng. Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all. *arXiv.org*, December 2012.

[7] B Ketzer, S Bachmann, M Capeans, M Deutel, J Friedrich, S Kappler, I Konorov, S Paul, A Placci, K Reisinger, L Ropelewski, L Shekhtman, and F Sauli. GEM Detectors for COMPASS. *IEEE Trans. Nucl. Sci.*, 48:1065–1069, 2001.

[8] B Ketzer. Micropattern Gaseous Detectors in the COMPASS Tracker. *Nucl.Instrum.Meth.*, A494:142–147, 2002.

[9] D Neyret, P Abbon, M Anfreville, Y Bedfer, E Burtin, and others. New pixelized Micromegas detector with low discharge rate for the COMPASS experiment. *Phys.Rev.*, 7:C03006, 2012.

[10] F Thibaud, P Abbon, V Andrieux, M Anfreville, Y Bedfer, and others. Performance of large pixelised Micromegas detectors in the COMPASS environment. *JINST*, 9:C02005, 2014.

[11] F J Iguaz, S Andriamonje, F Belloni, E Berthoumieux, M Calviani, and others. New developments in Micromegas Microbulk detectors. *Phys.Rev.*, 37:448–455, 2012.

[12] A Tomas, S Aune, T Dafni, G Fanourakis, E Ferrer-Ribas, and others. CAST microbulk micromegas in the Canfranc Underground Laboratory. *Phys.Rev.*, 37:478–482, 2012.

[13] E Ferrer-Ribas, D Attie, D Calvet, P Colas, F Druillole, and others. Micromegas detector developments for MIMAC. *Phys.Rev.*, 53:165–171, 2012.

[14] G Iakovidis. The Micromegas Project for the ATLAS Upgrade. *Phys.Rev.*, 8: C12007, 2013.

[15] C Adloff, M Chefdeville, A Dalmaz, C Drancourt, R Gaglione, N Geffroy, J Jacquemier, Y Karyotakis, I Koletsou, F Peltier, J Samarati, and G Vouters. Test in a beam of large-area Micromegas chambers for sampling calorimetry. *arXiv.org*, May 2014.

[16] Samuel Andriamonje, Gregory Andriamonje, Stephan Aune, Gilles Ban, Stephane Breaud, and others. New neutron detector based on Micromegas technology for ADS projects. *Nucl.Instrum.Meth.*, A562:755–759, 2006.

[17] I Giomataris, R De Oliveira, S Andriamonje, S Aune, G Charpak, P Colas, G Fanourakis, E Ferrer, A Giganon, Ph Rebourgeard, and P Salin. Micromegas in a bulk. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 560(2):405–408, May 2006.

[18] J Burnens, R De Oliveira, G Glonti, O Pizzirusso, V Polychronakos, G Sekhniaidze, and J Wotschack. A spark-resistant bulk-micromegas chamber for high-rate applications. *arXiv.org*, November 2010.

[19] M Byszewski and J Wotschack. Resistive-strips micromegas detectors with two-dimensional readout. *JINST*, 7:C02060, 2012.