**Commercial and Cost Effective Production
of
Two-Dimensional Read-Out Boards
for
Sub-Atomic Particle Detectors**

DOE Award Number: DE-SC0000917

Award Recipient: Tech-Etch, Inc.

Principal Investigator: David Crary

**Team Members: Yale University, Brookhaven National
Labs, Massachusetts Institute of Technology (MIT)**

SBIR/STTR RIGHTS NOTICE: These SBIR/STTR data are furnished with SBIR/STTR rights under Grant No. DE-SC0000917. For a period of four (4) years after acceptance of all items to be delivered under this grant, the Government agrees to use these data for Government purposes only, and they shall not be disclosed outside the Government (including disclosure for procurement purposes) during such period without permission of the grantee, except that, subject to the foregoing use and disclosure prohibitions, such data may be disclosed for use by support contractors. After the aforesaid four-year period, the Government has a royalty-free license to use, and to authorize others to use on its behalf, these data for Government purposes, but it is relieved of all disclosure prohibitions and assumes no liability for unauthorized use of these data by third parties. This Notice shall be affixed to any reproductions of these data in whole or in parts.

Abstract

We report results from research aimed at developing and demonstrating production of 2-D readout structures for GEM (Gas Electron Multiplier) charged particle tracking chambers at Tech-Etch. Readout boards of two types, bi-planar and single plane, were fabricated and evaluated. The results show that Tech-Etch can produce suitable boards of either type however the single plane board has a number of advantages both in production and use that will likely make it the preferred choice for GEM tracking chambers.

1 Executive Summary

The nuclear and high energy physics research community is constantly searching for new and improved tracking and radiation detectors. The introduction of micropattern detectors has opened new opportunities for improving the rate capabilities, as well as the spatial and time resolution of particle detectors in these applications. GEM detectors are now in use on many other nuclear and high energy experiments, around the world, including experiments at RHIC, JLAB, the LHC, and the STAR and PHENIX experiments at RHIC, future upgrades at the LHC, and at the proposed International Linear Collider. They are also plans for use of micropattern detectors in the upgrades of the STAR and PHENIX experiments at RHIC, future upgrades at the LHC, and at the proposed International Linear Collider. GEM foils were, initially only produced only at CERN, but they are now becoming available from several just a few commercial suppliers throughout the world. including Tech-Etch is currently the only commercial supplier of GEMs in the United States. One of the desirable features of Since, in GEM tracking detectors, is that the readout board containing the charge collecting electrodes is totally separated from the gain mechanism (the GEM foils),. This it allows great flexibility in the readout configuration. In particular, the 2-D readout boards used in the COMPASS (orthogonal strips) experiment at CERN and planned for the STAR experiment's forward tracking upgrade (cylindrical geometry with radial and azimuthal strips) illustrate this flexibility. GEM chambers offer the possibility to have spatial resolution approaching that of silicon detectors but with fabrication and readout costs similar to gas detectors. It would therefore be of significant benefit to the research community to develop a cost effective commercial source of readout boards for GEM chambers with well understood performance.

Tech-Etch has considerable experience in numerous related high precision etched Kapton[®] products including production of GEM foils. The required precision and production process for 2-D readout boards is similar to that developed for GEM foil production. Additionally, Tech-Etch has strong ties with several research institutions (namely Brookhaven National Laboratory, MIT and Yale University) that can help design and evaluate the performance of the readout boards produced at Tech-Etch. Since Tech-Etch is a small company, it also has the capability to produce a large variety of part configurations, optimized for a particular customer's requirements.

We describe below general considerations for 2-D GEM readout boards and then list the tasks from the original proposal and give the primary results or conclusions for each.

One of the great advantages of using GEM for charged particle tracking chambers is that the readout structure is decoupled from the gas multiplication structure and its associated high voltage. This allows large flexibility in the design of the readout structure. The two dimensional bi-planar readout developed at CERN for the COMPASS experimentⁱ has gained wide acceptance. Figure 1, bottom panel, illustrates a version of this type of readout board used previously to test triple GEM chambers with GEM foils produced by Tech-Etch.ⁱⁱ

Figure 1. Details of 2-D bi-planar readout board used in prototype chambers.

We proposed to demonstrate production of the bi-planar structure at Tech-Etch and also an alternate single plane geometry where all charge collection elements are on the same side. In the single plane geometry, copper strips on a polyimide film form one coordinate while rectangular pads between the strips are connected by vias and routing traces on the back side of the film to form the other coordinate. This is illustrated in Figure 2.

Figure 2. Sketch of single plane geometry for 2-D readout. Blue features represent pads and strips on the top side of the board. The dashed red lines and circles represent traces on the bottom of the board and vias connecting the pads in vertical strips.

This geometry is of interest because it is easier to manufacture, easier to estimate the ratio of charge collected on the two coordinates (charge sharing ratio), can be used without a support board (less material in the active area) and gives more flexibility in routing signals to the readout electronics.

It is desirable to use the same electronics to read out both coordinates, therefore to maximize dynamic range the charge sharing ratio between the two coordinates should be close to one. In the case of the single plane board the charge sharing ratio can be easily estimated from the feature size whereas this is not the case for a bi-planar board since the two coordinates are at different heights. If more than one charged particle strikes a 2-D GEM tracking chamber at the same time, there will be ambiguities in pairing the signals between the two coordinates. Each signal on one coordinate must be considered as possibly pairing with every signal on the other coordinate. Since the signals for a correct pairing on the two coordinates come from the same electron cloud, the ambiguities can largely be resolved by requiring that the signal size on the two coordinates to be similar. This works well only if the charge sharing ratio between the two

coordinates is uniform across the readout board ($\pm 10\%$ is typically adequate). Thus, both the magnitude of the charge sharing ratio and its uniformity across a board are of interest.

Work Plan:

The work plan was to produce boards of two different geometries: a multi-plane variant (Figure 5), and a single plane variant (Figure 10). The multi-plane version had varying strip width and strip pitch across the board, yielding a gradient of trace widths and pitches. The single plane board had pads and strips of fixed dimension and pitch across the board.

After the initial production run was verified, the readout boards were sent to Yale, where they were incorporated into an existing GEM setup and tested, and will see interaction with an existing GEM foil setup. From these experiments, data was obtained and analyzed and the second production run was configured

The second run of readout boards concentrated primarily on reproducibility. Using the analysis from the first part of Phase I, multiple iterations, in fewer numbers than before, were produced. These boards were sent to the collaborating institutions, tested, and analyzed.

The second set of readout boards, which will be much fewer in quantity, will directly lead to the future production of a final readout board, as we feel that the knowledge gained from the two initial production runs will allow us to gain a reliable understanding of the manufacturing process and enable us to demonstrate reproducibility of the results. The Phase I Task Schedule is outlined in Table 1 below.

All aspects of the work plan were completed during the Phase I time period.

1.1 Technical Objectives

The specific goal of Phase I is to produce a series of readout boards that meet or exceed the performance required for use in a GEM tracking detector. Multi-plane and single plane boards with a variety of parameters will be evaluated for performance in GEM chambers, uniformity of physical parameters, ease of manufacture and reproducibility. The boards will be evaluated with optical measurements and operated in a GEM chamber to assess the uniformity and resolution. Also, the calculations used to estimate charge sharing will be vetted or tuned so as to provide a useful tool for understanding new layouts. Detailed measurements will be carried out by the research collaborators. BNL, MIT and Yale have significant experience in operating and characterizing the performance of GEM chambers using a variety of measurements with radioactive sources, X-ray machines, generators, cosmic rays and test beams. Also the collaborators can perform physical measurements with a variety of instruments including an OGP[®] coordinate measuring machine. The goal of Phase I is to understand the advantages and limitations of single plane and multi-plane boards produced with precision etching, and to develop the techniques that will later be used in production of the resulting readout structures.

1.2 Technical Objective 1. Produce and evaluate a variety of Bi-planar Boards.

Tech-Etch initially produced 3 bi-planar boards using the etched polyimide technique. These boards have fixed strip width and pitch (700 μm / 800 μm) on the bottom layer and 16 combinations of width and pitch on the top layer. Figure 3 illustrates the layout and details are in Table 1 (All Tables are located in Appendix A).

Naming convention used:

“Top” strips (T1-T4) are variable pitch and width, closest to GEM foils

“Bottom” strips (B1-B4) are fixed pitch and width, furthest from GEM foils.

Figure 3. Layout of bi-planar board. Each of the 16 areas (B1T1 - B4T4) in the active area (10 cm x 10 cm, shaded gray) has a different combination of strip width and pitch on the top layer. The bottom layer has fixed width and pitch (700/800 μm).

This pattern allows exploration of a variety of patterns on a single board to better understand the capability and limits of the technology and also gives a data set to compare measured charge sharing ratios with those expected from electrostatic calculations. From physical inspection of the boards it is clear that trace widths less than $\sim 70 \mu\text{m}$ are difficult to achieve. On two of the boards the copper on some of the thinnest traces is delaminated from the substrate. One board is suitable for use in a GEM chamber so the charge sharing ratio was measured for that board. Tech-Etch produced 3 more boards with the same pattern. These three boards have no issues with delaminating of thin traces. The thinnest traces however are still wider than specified, indicating again that strips less than $\sim 70 \mu\text{m}$ width are difficult to achieve. For these three boards, one board has one pair of (top/bottom) strips is shorted together. The other two boards have no flaws. All three of these boards were run with a GEM chamber to measure the charge sharing ratio. The results compare well with the expectation from electrostatic calculations provided the measured feature sizes are used in the calculations. This shows that electrostatic calculations are a useful tool for estimating the expected charge sharing ratio for bi-planar boards. The measurements (physical feature sizes and charge sharing ratios) are given in the sections below. They indicate that feature size – particularly strip width – is typically within 5% of specification for strips wider than $\sim 70 \mu\text{m}$.

Tech-Etch has demonstrated the capability to produce bi-planar 2-D readout boards suitable for use in a GEM tracking chamber.

1.3 Objective 2. Produce and evaluate a variety of Single Layer Boards.

To address this part of the project it was decided to produce boards at the limit of possible feature size even though this would likely reduce the yield. This approach would verify the limit of what is possible and expose possible difficulties in manufacturing the boards. Tech-Etch produced 6 boards with 300 μm pitch. We note that to achieve 300 μm pitch requires 80 μm wide strips and 60 μm gaps. Figure 4, right panel, shows a small part of one of these boards.

Figure 4. Single layer board with 300 μm pitch. Left panel: Board mounted on optical coordinate measuring machine at Yale. Right panel: image from measuring machine showing pattern. The rectangular pads are connected in columns by vias and routing traces on the opposite side of the board.

The two main problems seen on these boards are incomplete etching of the flash layer between the features and occasional local damage to a pad or strip. Two of the six boards have significant areas where the flash layer is incompletely etched. It is likely that this is due to the difficulty of fully etching the small gaps between features. The result is that for the areas with incomplete etching most or all features are shorted together.

Local damage to a pad or strip can result in molten copper droplets being deposited nearby sometimes shorting a trace from one coordinate to the neighboring trace or pad. The 4 boards with complete etching of the flash layer all have some shorts between single lines on the two coordinates. These boards are still useable with only a small loss of efficiency. The charge sharing measurement was made on one of them. For all boards the feature sizes are as specified and the charge sharing the ratio is as expected for the feature sizes. Since both of the observed fabrication problems are greatly reduced or not present for larger pitch, and since GEM chambers with pitches of 400-600 μm have already demonstrated excellent spatial resolution^{i, ii} it is likely that single plane boards will be preferred for GEM readout boards. Details of the measurements on these boards are given below. After completion of this SBIR, single plane boards with 800 μm pitch have been produced for a customer order. These boards have no flaws.

1.4 Overview.

Tech-Etch produced 6 bi-planar boards with the pattern shown in Figure 3 and Table 1 and 6 single plane boards with 300 μm pitch. All boards have 10 cm x 10 cm active area. For each set the following steps were performed to evaluate the boards:

- The entire surface of each board was scanned on the Yale optical coordinate measuring machine at low magnification (33x). For any flaws or unusual features the position and an image were recorded.
- The feature sizes and pitch were measured in selected places. For the bi-planar boards measurements were taken in the center of each of the 16 regions. For the single plane boards measurements were taken at 12 locations across the board.
- A subset of boards was assembled into triple GEM chambers and a ^{55}Fe radioactive source used to measure the charge sharing ratio in several regions of the board.

Details of all measurements for the two types of readout board are given in the following sections.

1.5 Bi-Planar Boards.

The patterning on these boards is shown in Figure 3 and Table 1.

1.5.1 Surface scan.

Two of the first 3 boards delivered show some delaminating of the thin traces (see Figure 5).

Figure 5. Images showing delamination of copper for thinnest strips in the “B1T1” region of the board. Left is image from coordinate measuring machine, right is digital photo.

For these strips, nominally only 50 μm wide, etching away all the polyimide between the strips so as to fully expose the bottom layer while still leaving sufficient support for the top trace is challenging. The second set of three boards delivered does not show any delamination. Figure 6 shows images from the coordinate measuring machine for 4 regions in a bi-planar board. The dark “shadows” on either side of the top strips (running horizontal) are the polyimide supporting the top strips.

Figure 6. Images of 4 regions from a bi-planar board from coordinate measuring machine. Note: magnification is less for bottom two. Variable width and pitch (top) strips are horizontal. Fixed width and pitch (700/800 μm) strips run vertical.

1.5.2 Feature sizes.

For the 4 boards with no delamination, the strip widths and pitches were measured in the 16 different regions. We note that the coordinate measuring machine has a resolution of 0.5 μm however since the edges of the strips are slightly irregular, a natural consequence of the etching process, the setting error to find an edge is $\sim 5 \mu\text{m}$. The results are given in Table 2 along with the averages across the 4 boards and the nominal values. The measurements show reasonable correspondence to the nominal values.

1.5.3 Charge sharing ratios.

Four of the boards were assembled at Yale into a triple GEM chamber and tested with a ^{55}Fe radioactive source. For these tests the signal from the bottom of the last GEM foil (closest to the readout board) is used for a trigger. About 1/3 of the charge exiting the holes in the last foil curls back onto the foil and can be used to trigger the digitization of all pulses. For these tests, the bottom strips are ganged together into 4 groups and the top strips are also ganged into 4 groups – representing the 16 regions of pitch and width with only 8 channels of readout. The gains for all eight readout channels were calibrated and shown to be equal to a few per cent.

The chambers were tested in a stainless steel test vessel filled with 1 atm. of 90% Ar, 10% CO_2 . Typical pulse height spectra are shown in Figure 7.

Figure 7. Typical pulse height spectra from bi-planar readout board assemble in a triple GEM chamber. The top panel is the signal from the bottom of the last GEM foil (used as a trigger signal), bottom panel is from group T3. The main peak represents the energy deposited by the 5.9 keV X-ray from the ^{55}Fe source used for these tests. The smaller peak to the left is the Argon escape peak resulting from a 2.9 keV argon fluorescence X-ray escaping the detector. Fits to the main peak give energy resolution of $\sim 15\%$ for the last foil and 12% for the readout board strips.

The energy resolution is typical for a gas detector and indicates the chambers are performing properly. Events are selected that meet the following criteria:

- One of the 4 groups of top strips, one of the 4 groups of bottom strips and the last GEM foil have a pulse height above pedestal noise and below the maximum expected from the ^{55}Fe X-ray.
- No other channels have a signal above pedestal
- The ratio of the summed strip pulse height (top + bottom) to the last foil pulse height is within a narrow band. (See Figure 8)

Figure 8. Typical distribution of the ratio of (top strip pulse height + bottom strip pulse height) to (last GEM foil pulse height) (black). The red overlay shows the region selected for analysis. The low side tail results from cosmic rays crossing more than one region and X-ray signals near the region boundary leaving some charge in a neighboring region.

These cuts help eliminate events where signals on the readout board are shared between neighboring regions. This results from X-ray signals near the region boundary or cosmic rays crossing more than one region.

Finally, the ratio of top strip pulse height to bottom strip pulse height is plotted for all 16 regions and the central peak is fit with a Gaussian shape to extract the charge sharing ratios between the two coordinates. Figure 9 shows the correlations (scatter plot) between top and bottom strips for four of the 16 regions and Figure 10 shows the distribution of the ratios for the same 4 regions. Table 3 gives the measured charge sharing ratios for all 16 regions of the 4 boards tested. Also shown are the averages across the 4 boards, the calculated ratios from an electrostatic field calculation using the measured feature sizes as input and the ratio between the measured and calculated values.

Figure 9. Correlation between top strip pulseheight and bottom strip pulse height for four of the 16 regions. Black = B1T1, red = B2T1, blue = B3T1, magenta = B4T1.

Figure 10. Distribution of pulse height ratios for the same regions shown in Figure 9.

1.5.4 Conclusions for Bi-Planar Boards.

The first batch of boards shows some delaminating of the thinnest traces. It is likely to prove challenging to manufacture boards with trace widths similar to the thickness of the polyimide substrate. Charge sharing ratios between the two orthogonal coordinates measured over a variety of strip widths and pitches agree reasonably well with values expected from electrostatic calculations. Tech-Etch has demonstrated the capability to produce bi-planar readout boards for GEM tracking chambers with a large variety of feature sizes.

1.6 Single Plane Boards.

Tech-Etch produced 6 single plane boards with 300 μm pitch. These boards were evaluated at Yale following the same steps used for the bi-planar boards. Figure 4 shows one board mounted on the coordinate measuring machine at Yale (left panel) and an image from the measuring machine of a small section of the board (right panel).

1.6.1 Surface Scan.

Features found scanning the full surface of all boards fall into two categories. First, on some regions of some boards the copper between the pads and strips was not completely etched away (Figure 11, left panel).

Figure 11. Features found in full surface optical scan of single plane 300 μm pitch boards. Left panel: conductor between pads and strips not completely etched. Right panel: Local damage to pad and strip with copper slag possibly shorting the two together.

This indicates the difficulty of etching such small gaps. Since the remaining copper results in many traces being shorted together these boards are not useable. The other feature is local damage to one pad or strip or neighboring combination as illustrated in Figure 11, right panel. Here there is some copper slag likely shorting the pad to the strip. These features are less serious and result only in a small inefficiency.

1.6.2 Feature Sizes.

Strip width and pitch and pad height, width and pitch were measured in 12 locations on one board. The results are shown in Table 4. To within the setting errors, the feature sizes are as expected and uniform across the board.

1.6.3 Charge Sharing Ratios.

One of the 300 μm pitch single layer boards was assembled into a triple GEM chamber and the charge sharing ratio between the coordinates was measured for 12 regions (corresponding to the places the feature sizes were measured, Table 4) using the same technique described in section 1.5.3. The results are given in Table 5 along with the average value, standard deviation, and the ratio expected from the measured and nominal feature sizes. All agree remarkably well. Although there is some variation among the 12 regions it is not correlated with feature size and is largely within what is expected from the accuracy in determining the charge sharing ratio.

1.6.4 Conclusions for Single Plane Boards.

Boards produced with 300 μm pitch are at the limit of feature size for this technique. Useful boards can be produced and show good uniformity of feature size and charge sharing ratio. Given that for most applications coarser pitch and larger features are used (and even beneficial in reducing the number of readout channels), it is expected that single plane boards can be produced with high yield (see note *Error! Bookmark not defined.* above). Bi-planar boards with a pitch of 635 μm have been shown previously to give a spatial resolution for high energy charged particles of 70 μm .ⁱⁱ Simpler fabrication, lower cost, greater flexibility in routing signals to the readout electronics and lower mass in the active region all make the single plane boards a more attractive choice for GEM readout.

2 Conclusions.

The research carried out under this grant allowed development and evaluation of the capability at Tech-Etch to produce 2-D readout boards for GEM tracking chambers. Tech-Etch has demonstrated the capability to produce both bi-planar and single plane boards. The demonstration that single plane boards can be produced that perform well in a triple GEM detector will benefit all users of GEM tracking chambers by providing a less costly, simpler, more flexible option for 2-D readout boards. After the conclusion of the performance period for this grant, Tech-Etch produced single layer 10 cm x 10 cm boards with 800 μm pitch for MIT and has received an order for larger single layer boards with a cylindrical-coordinate geometry for the STAR FGT upgrade.

APPENDIX A

TABLES

	B1		B2		B3		B4	
	Strip Width	Pitch	Strip Width	Pitch	Strip Width	Pitch	Strip Width	Pitch
T1	50	275	60	400	70	525	80	650
T2	70	275	80	400	90	525	100	650
T3	90	275	100	400	110	525	120	650
T4	110	275	120	400	130	525	140	650
Bottom	700	800	700	800	700	800	700	800

Table 1. Nominal feature sizes and pitches for bi-planar board. All dimension are microns.

		Strip Width						Strip Pitch					
Position		CS1	CS4	CS5	CS6	Ave	Nom	CS1	CS4	CS5	CS6	Ave	Nom
B1	T1	70.0	69.3	43.9	69.3	63.1	50	273.0	275.2	276.0	275.2	274.8	275
B1	T2	70.0	73.5	68.8	73.5	71.4	70	395.0	400.5	397.5	400.5	398.4	400
B1	T3	87.0	92.5	88.6	92.5	90.2	90	521.0	525.5	523.9	525.5	524.0	525
B1	T4	113.0	103.5	106.5	103.5	106.6	110	648.0	645.5	647.3	645.5	646.6	650
B2	T1	79.5	71.0	60.4	71.0	70.5	60	274.5	276.0	275.9	276.0	275.6	275
B2	T2	80.0	79.5	82.4	79.5	80.3	80	399.0	398.5	399.9	398.5	399.0	400
B2	T3	103.0	103.0	100.5	103.0	102.4	100	520.0	526.0	524.0	526.0	524.0	525
B2	T4	124.0	115.0	118.9	115.0	118.2	120	647.0	647.0	649.8	647.0	647.7	650
B3	T1	79.0	81.0	73.6	81.0	78.7	70	274.0	277.0	275.3	277.0	275.8	275
B3	T2	87.5	95.5	87.8	95.5	91.6	90	400.5	403.5	399.5	403.5	401.7	400
B3	T3	105.5	103.0	110.0	103.0	105.4	110	521.5	525.0	521.3	525.0	523.2	525
B3	T4	134.5	128.0	125.6	128.0	129.0	130	649.5	651.0	648.9	651.0	650.1	650
B4	T1	84.5	89.0	77.3	89.0	84.9	80	273.5	270.0	272.8	270.0	271.6	275
B4	T2	98.5	104.0	95.9	104.0	100.6	100	398.5	403.0	400.4	403.0	401.2	400
B4	T3	126.0	122.0	118.5	122.0	122.1	120	521.0	526.0	524.8	526.0	524.4	525
B4	T4	142.0	131.0	139.0	131.0	135.8	140	647.0	646.0	649.9	646.0	647.2	650
Bottom		705.5	700.1	704.2	700.1	702.5	700.0	799.7	799.8	799.4	799.8	799.7	800

Table 2. Measured strip widths and pitches for four bi-planar readout boards (designated CS1, CS4, CS5, CS6). The measurements are made for each of the 16 regions (designated in the left acolumns as B1,T1 to B4,T4) and for the bottom fixed with strips. the average across the 4 boards and the nominal values are in bold. All dimensions are in microns.

Position		CS2 ratio (Top/Bot)	CS4 ratio (Top/Bot)	CS5 ratio (Top/Bot)	CS6 ratio (Top/Bot)	Ave	T/B for Meas Geom from Electrostatics calc	Ave/ Electrostatics
B1	T1	242	225	254	222	236	291	081
B1	T2	155	144	156	144	150	136	1.10
B1	T3	118	111	118	107	114	099	1.15
B1	T4	097	093	099	092	095	084	1.13
B2	T1	299	270	307	297	293	322	091
B2	T2	180	164	174	178	174	151	1.15
B2	T3	136	127	132	134	132	114	1.16
B2	T4	111	106	110	116	111	089	1.24
B3	T1	308	275	307	274	291	322	090
B3	T2	173	156	165	153	162	157	1.03
B3	T3	131	121	125	116	123	114	1.08
B3	T4	105	100	103	100	102	096	1.06
B4	T1	326	296	333	334	322	357	090
B4	T2	184	169	175	185	178	183	097
B4	T3	138	129	130	136	133	134	099
B4	T4	111	106	107	116	110	101	1.09

Table 3 Charge sharing ratios between the two coordinates for all 16 regions on 4 bi-planar readout boards. Also shown (3rd from last column) are the averages across all 4 boards, (2nd from last column) the ratio expected from electrostatic calculation using the measured feature sizes as input, and (last column) the ratio measured to expected

Label		Location(m)		Strip		Pad		
Pad	Strip	X	Y	Width (μm)	Pitch(μm)	height(μm)	length(μm)	Pitch(μm)
1	1	105	735	800	3060	1025	2430	3040
1	2	105	525	820	3110	1010	2445	3055
1	3	105	315	805	3065	1075	2435	3055
1	4	105	105	825	3085	1030	2440	3040
2	1	315	735	785	3085	1015	2405	3055
2	2	315	525	785	3005	990	2385	3065
2	3	315	315	800	3080	1005	2395	3015
2	4	315	105	745	3015	975	2400	3070
3	1	525	735	785	3065	995	2435	3065
3	2	525	525	730	3020	1005	2400	3050
3	3	525	315	770	3050	995	2395	3015
3	4	525	105	775	3025	1025	2420	3090
Average				785	3047	1012	2415	3051
St. Dev.				28	31	26	21	22
Nominal				800	3000	1000	2400	3000

Table 4 Features sizes measured on one single layer board. Location of the measurement (m) is referred to the lower left edge of the active area (see Figure 3). All other dimensions are in microns.

Location		Ratio
Pad	Strip	Strip/Pad
1	1	0.886
1	2	0.823
1	3	0.902
1	4	0.860
2	1	0.935
2	2	0.873
2	3	0.975
2	4	0.876
3	1	0.852
3	2	0.790
3	3	0.868
3	4	0.785
Ave		0.869
St. Dev.		0.055
Expected From Measured Feature sizes		0.862
Expected From Nominal sizes		0.875

Table 5. Charge sharing ratios (strip/pad) for a single layer 300 μm pitch board. The 12 regions correspond to the places the feature sizes were measured (Table 4).

References

- i. C. Altunbas, *et al.*, *Construction, test and commissioning of the triple-gem tracking detector for compass*, Nucl. Instrum. and Meth. in Physics Research A 490 (2002) 177–203
- ii. F. Simon, *et al.*, *Beam Performance of Tracking Detectors with Industrially Produced GEM Foils*, Nucl. Instrum. and Meth. in Physics Research A 598 (2009) 432–438