GEM TN-93-281
Draft

Proposal to Use Separated Profile Strip Chambers for the GEM Muon System

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Abstract:

A report is presented on (a) Results of tests of the Separated Profile Strip Chamber prototype, (b) A cost estimate of the GEM muon barrel in this strip geometry and (c) other specific technical questions. Parts (b) and (c) are compared, where possible, to the MWPC geometry. This is a draft of work in progress.

DRAFT

Table of Contents

Note: Sections and Tests Not Yet Completed Include Trigger tests, neutron efficiency, further HV studies, alternate gases, ...

Sec. I. Introduction

The case for using strip chambers in the GEM muon detector was presented in GEM-TN-92-199 and additional comparisons were made to other technologies in early 1993.

The purpose of this document is to discuss the relative characteristics of the two proposed technologies within the strip technology. One of these involves multi wire proportional chamber (MWPC) geometry, and the other involves separated profile chamber (SPC) geometry. These technologies differ in many variables, such as resolution, stability of resolution against HV, assembly tolerances, cost, neutron efficiency, radiation length thickness, trigger timing characteristics, repairability, amenability to commercial production, lifetime, ease of shipment, and operating costs.

We present here a comparison of the two strip chamber technologies. Many non trivial questions are involved. Some of these have only recently emerged. Where possible, we rely upon experimental data in the comparison. Because prototypes are involved, and these are in the early stages of testing, even the experimental data may change.

Some key tests are not yet completed. We are dealing in some cases with some questions not yet experimentally tested, and preconceived notions may prove wrong. In this note, we look at the current situation. *This note, in order to be timely, is necessarily incomplete.* Work on this note is continuing.

We assume in the following an 8 6 6 base line. However, in Sec. III (Cost Estimates), in order to make comparisons to previously reported MWPC cost estimates based on an 844 geometry we also calculate costs based upon an 844 geometry. We assume supports as in document TN-92-199, with separated profile super chambers bolted together in the same way as are MWPC super chambers.

For convenience of the reader, we summarize, in Table I.1, our initial conclusions from Sec.'s II, III, and IV of the report.

Table I.1
(As of 1/8/93)

Comparison Variables	Separated Profile Chambers	Multi Wire Proportional Chambers
Best case Resolution		
Using ± 6°	56.4 μm	65 μm
Using ± 2°	(38 ± 3 μm)	(50μm) angular interval = ?
Voltage Instability of Resolution $\left(\frac{d\sigma}{\sigma} \middle/ \frac{d\text{HV}}{\text{HV}}\right)$	9.5	26
Automated Production	Yes, about 90%	No
Anode Stability	Supported as desired	Full length unsupported
Anode Criticality	Specification ± 200μm	Specification ± 20μm
Wire breakage protection	yes	No
Repair of broken wire	< $100	$4,000?
Survival in shipping	excellent	?
neutron efficiency	~0.28%	~0.22%
Thickness (rad.l)	1.58%/layer	0.9%/layer
Lifetime (relative)	29 years	51 years
Trigger efficiency	?	80%/layer
Cost estimate (materials, assembly, and contingency)	$15.956 million	$38.771 million
Losses in Shipping	≤ 0.4%	?

Sec. II. The UH CSC Prototype

II.1 Construction

The UH CSC prototype consists of three precision strip planes[(1)]. The active area for each plane is 0.5 x 1.0 m^2. Each strip plane is composed of a $^1/_{16}$" double-sided copper-clad FR 4 board (copper thickness = 0.5 oz/ft^3), epoxied to a 0.48" thick 2' x 4' honeycomb panel. The copper strips are 4 mm wide and 1.0 m long, separated by a 1.0 mm gap. The copper on the other side of the FR 4 board serves as an electrical shield. The strip boards were manufactured by MPC at Lowell, Mass by lithographic techniques. The pitch of the copper strips is determined by the accuracy of the photo-plotting and was designed to be 5 mm.. Actual measurements showed that the pitch is constant to within 1 μm (systematic) with a random error of no more than 15 μm, although the widths of the copper strips were controlled to only ± 25 μm in the photo-etching process. A plot of the survey data for the pitch is shown in Fig. II.1.1. The actual pitch was 4.999 μm.

The internal alignment of the three strip boards was achieved by inserting 1/2" ground SS rods through 4 sets of precision holes, one at each corner of the honeycomb panel. These alignment holes were accurately referenced (± 25 μm) to fiducial marks etched on the strip boards. Cosmic-ray results (see sec. II.4) showed that the middle plane is off by 33 ± 5 μm, in agreement with the expected precision of this procedure. The GEM muon system requirement calls for 50 μm internal alignment accuracy.

The signal-producing chambers are 66 cm long and were constructed as standard Iarocci-type PVC open-profiled chambers. See Fig. IV.1.2. Each chamber consists of eight U-shaped 9 mm x 9 mm cells separated by 1 mm thick walls, encapsulated in a common gas volume. The PVC walls were coated with graphite with an average resistivity of 4kΩ/□. The uniformity of the graphite coating is important to the resolution and was controlled to ± 10%. The anode wires are gold-plated tungsten with a diameter of 0.00175" (44.5 μm), suitable for proportional mode operation.

The chambers were placed between the honeycomb panels, running orthogonal to the strips. (See Fig. II.1.2) The positioning of the open profile chambers are less critical than that of the strips. An alignment of ± 10 mrad was achieved. The twelve chambers in each layer share the same gas and high voltage. The chambers were operated in a gas mixture of 25% argon and 75% isobutane with high voltage ranging from 3.1 to 3.3 kV, for the results reported here.

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(1) The desired fourth plane was precluded by budget considerations.

Fig. II.1.1

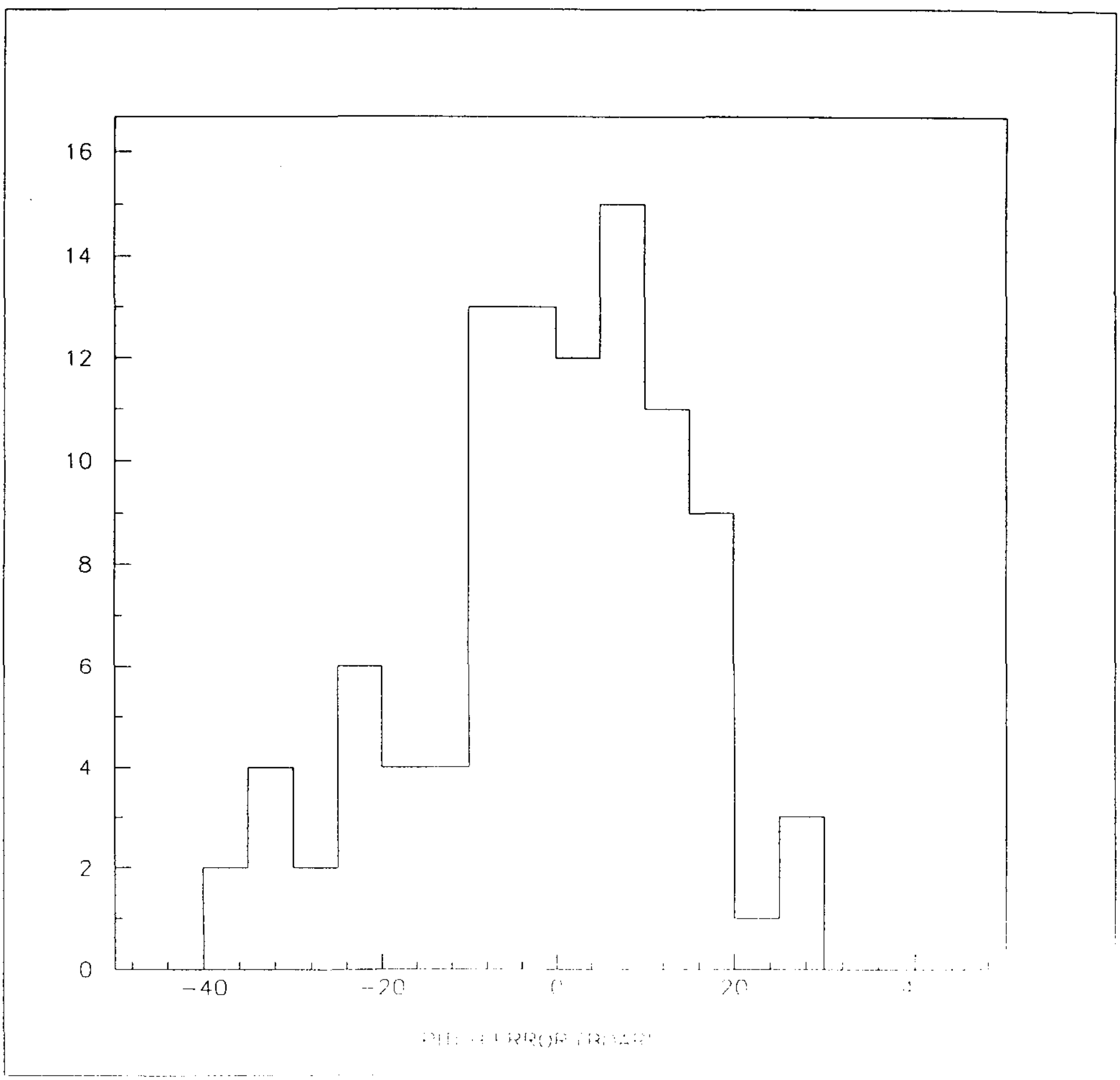
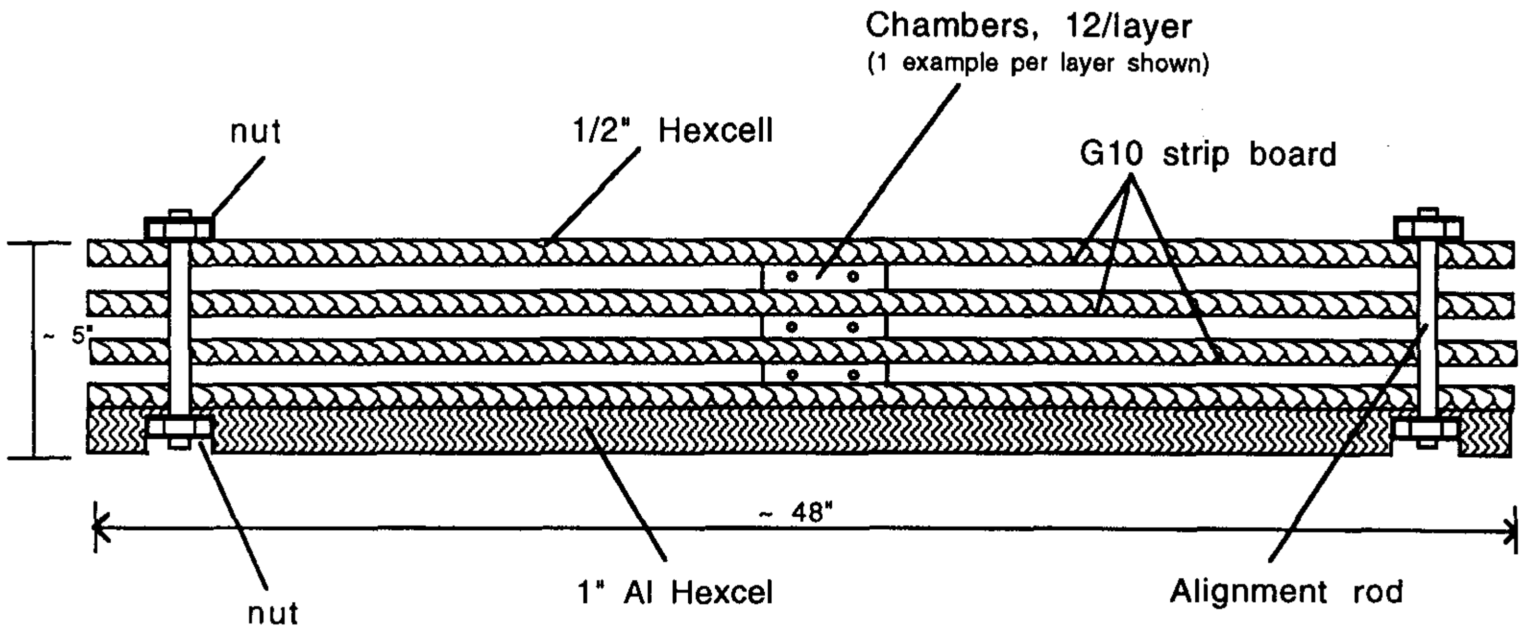


Fig. II.1.2

Side View of UH CSC Prototype



University of Houston

II.2 Electronics

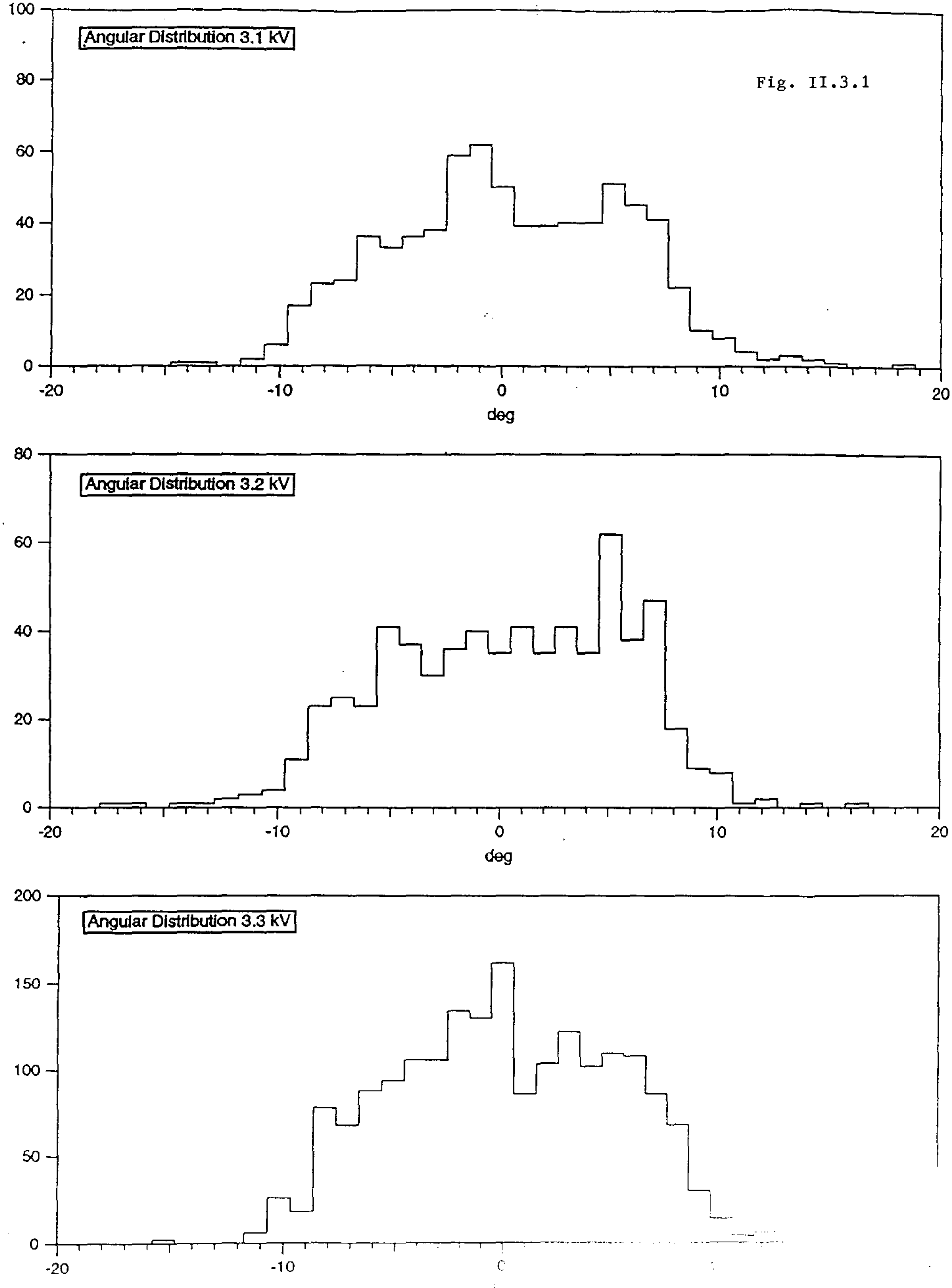
The UH CSC prototype provides coordinate measurement along the anode wire, which relies on precision measurement of charge induced on the precision strips. In order to obtain a spatial resolution under 75 μm for 5 mm pitch strips, a signal-to-noise ratio of better than 100:1 has to be maintained.

Thirty strips, ten from each layer, near the center of the prototype were instrumented with charge-sensitive preamplifiers (preamps), one channel for each strip. (We were not able to instrument the entire prototype due to the shortage of electronics.) The preamps were designed and home-built by Dubna. These preamps feature low noise (~2,000 e's), high gain (~2,000), and independent calibration for each channel. The preamps were mounted in two electrically shielded boxes which are located near one end of the strips. The strips were soldered to the input cables (RG 174) of the preamps. The output signals were routed via 53 m long RG 174 coaxial cables to CAMAC charge-integrating LeCroy Model 2249W ADC's. The long signal cable length is the result of a 225 ns delay in the trigger. The 11-bit 2249W's provide adequate dynamic range to allow the chambers to operate with gas gains in the range 10^4 - 10^5. The integration time was set to 500 ns for most of the measurement, even though some exploratory runs were taken with a 400 ns integration time. This seemingly long integration time was chosen to take into account the shaping time of the preamp (~ 300 ns) and drift-time jitter (~ 100 ns) in the chambers. An additional 100 ns was added to safe-guard against possible error in the timing.

II.3 Test setup

The results reported here were obtained at the Texas Test Rig in the SSCL. A 1.0 m thick iron magnet near the bottom of TTR ensures a muon momentum above 1.5 GeV/c. The multiple Coulomb scattering in the UH prototype for 1.5 GeV/c muons contributes ~ 20 μm to the resolution, which is small compared to the expected intrinsic resolution. A somewhat more restrictive trigger, which demands a coincidence of two of six top scintillators and all scintillators at the bottom of TTR, was used for muon selection. This trigger enhances the fraction of events in which the muon traversed the instrumented strips. This trigger limits the azimuthal incident angle of the muons ϕ to $\pm 8°$, resulting in a muon illumination similar to that of the GEM muon chambers (Baseline 2) at the SSC . (See Fig. II.3.1). The resolution is insensitive to the polar angle of the muons.

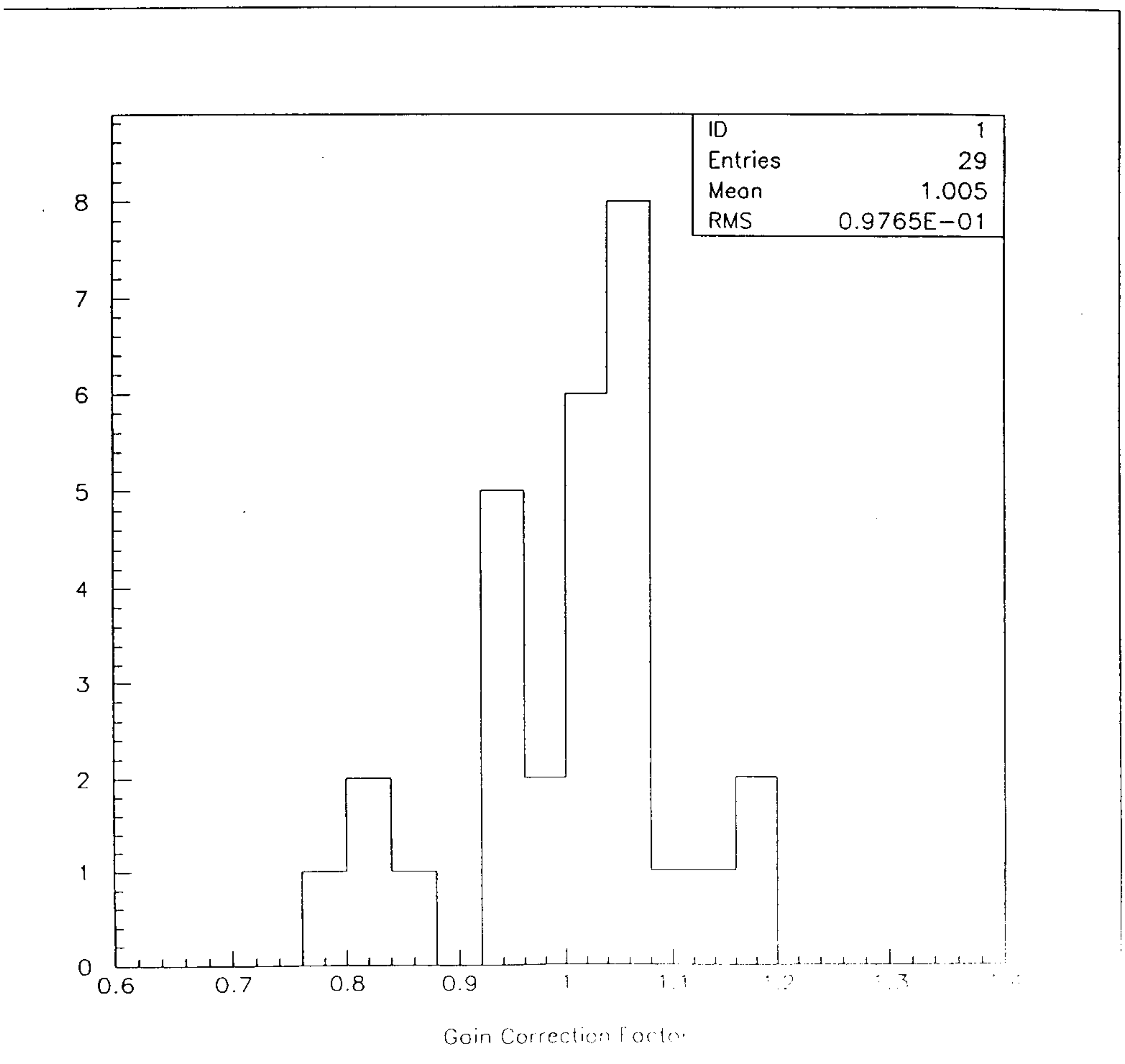
We have taken data at several high voltages for the chambers. Between data runs, we took calibration runs in which test pulses were injected and distributed equally to all the 16 channels in each box. This provides relative gain measurements for the 16 channels in a box. A histogram of the uncorrected relative gains, which are normalized to 1, is shown in Fig. II.3.2a. We determine



Angular Distribution 3.1 kV
100
80
60
40
20
0
-20
-10
0
10
20
deg
Angular Distribution 3.2 kV
80
60
40
20
0
-20
-10
0
10
20
deg
Angular Distribution 3.3 kV
200
150
100
50
0
-20
-10

Fig. II.3.1

Fig. II.3.2a



ID 1
Entries 29
Meon 1.005
RMS 0.9765E-01
0
1
2
3
4
5
6
7
8
0.6
0.7
0.8
0.9
1
1.1
Goin Correction

the pedestal of each ADC channel by using events in which the muon did not go through the instrumented strips. Fig. II.3.2b shows the raw ADC counts for such events. It shows a pedestal of 40 ADC counts and a noise of ~ 5 ADC counts.

II.4 Data Analysis and Results

We determine the spatial resolution of the prototype by reconstructing the muon trajectories. We select events with at least 100 raw ADC counts in each layer to ensure that a muon went through the instrumented strips. About 5% of the triggers satisfied this requirement. We also require the peak channel to be at least 2 channels away from the acceptance boundary. We exclude events in which the peak channel exceeded the dynamic range of the ADC (2,000 counts). The total pulse height for each layer, obtained by adding the ADC counts of four contiguous strips, are shown in Figs II.4.1a, b, and c, as a function of high voltage. The spectra appear to be in agreement with a Landau distribution. More detailed comparison is in progress.

We reconstruct the muon trajectory by finding the centroid of the charge profile in all three planes. Specifically, the charge centroid Z_{cog} is defined to be

$$Z_{cog} = \frac{Z^{(3)}}{1 + \frac{2}{W}\left(Z^{(3)} - Z^{(4)}\right)}, \tag{1}$$

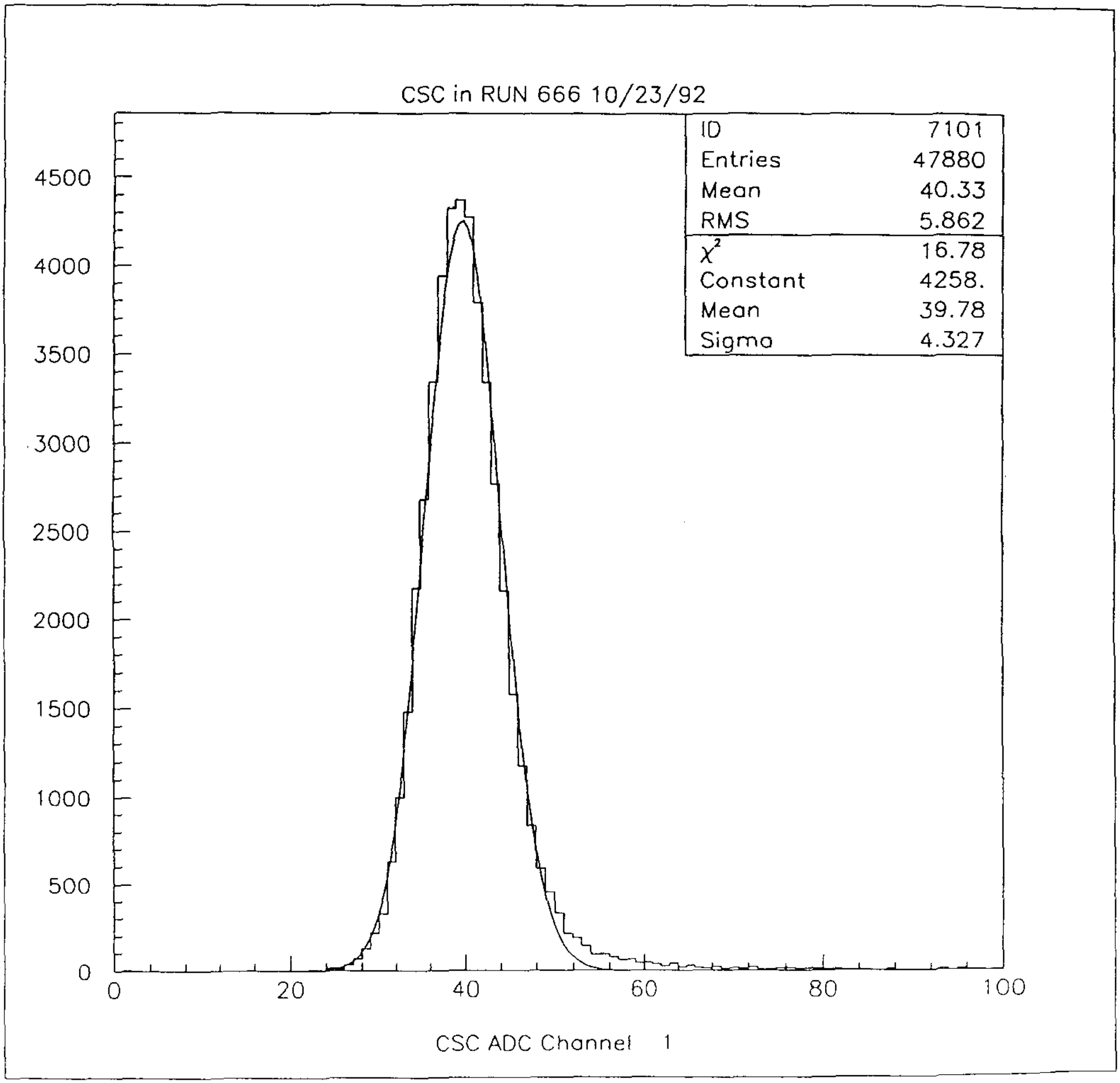
where $Z^{(3)} = \sum_{i=1}^{3} Z_i Q_i \Big/ \sum_{i=1}^{3} Q_i$ and $Z^{(4)} = \sum_{i=1}^{4} Z_i Q_i \Big/ \sum_{i=1}^{4} Q_i$, respectively. $Z^{(3)}$ and $Z^{(4)}$ are the center-of-gravities using 3 strips and 4 strips, respectively. Q_i are pedestal-subtracted and gain corrected. W is the pitch of the strips.

The algorithm (see equation ((1)) is chosen because it reproduces the exact muon positions at Z=0 (muon going through the center of the strip) and Z =$^1/_2$W (muon going through between 2 strips). This algorithm also minimizes the systematic difference between Z_{cog} and the actual muon position (Z_{real}) for 0 < Z < $^1/_2$ W. We studied the systematic correlation between Z_{cog} and Z_{real} and found that the correction can be described by a 3-term Fourier series.

$$\Delta Z = A\left[\sin\left(\frac{2\Pi\, Z_{cog}}{W}\right) - 0.077\sin\left(\frac{4\Pi\, Z_{cog}}{W}\right) + 0.041\sin\left(\frac{6\Pi\, Z_{cog}}{W}\right)\right]$$

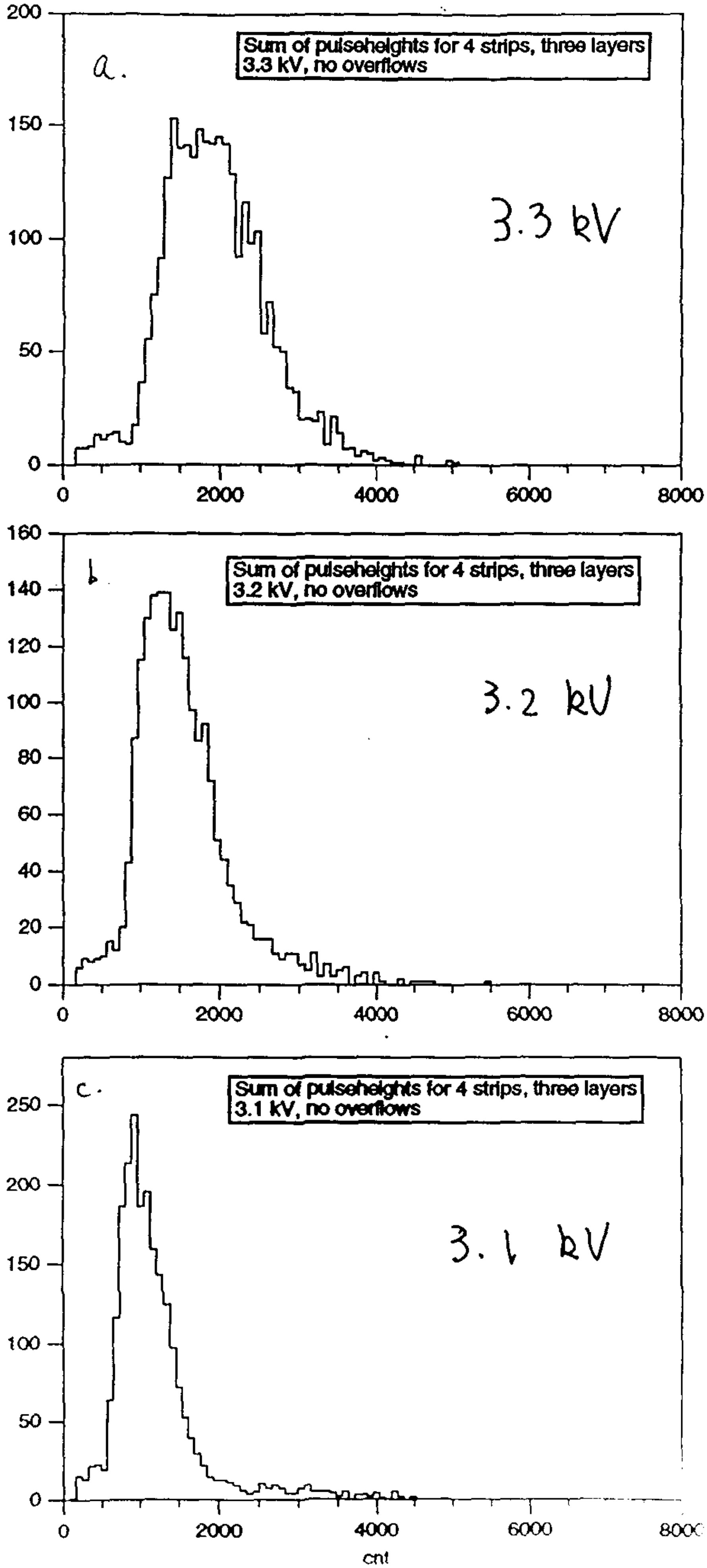
The exact function and the 3-term approximation are shown in Fig. II.4.2. The amplitude A is varied to obtain a best fit to the data. A typical value for A is 90 μm, in agreement with monte carlo simulation which predicts A = 110 μm.

Fig. II.3.2b



CSC in RUN 666 10/23/92
ID 7101
Entries 47880
Mean 40.33
RMS 5.862
χ² 16.78
Constant 4258.
Mean 39.78
Sigma 4.327
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
20
40
60
80
100
CSC ADC Channel 1

Fig. II.4.1abc



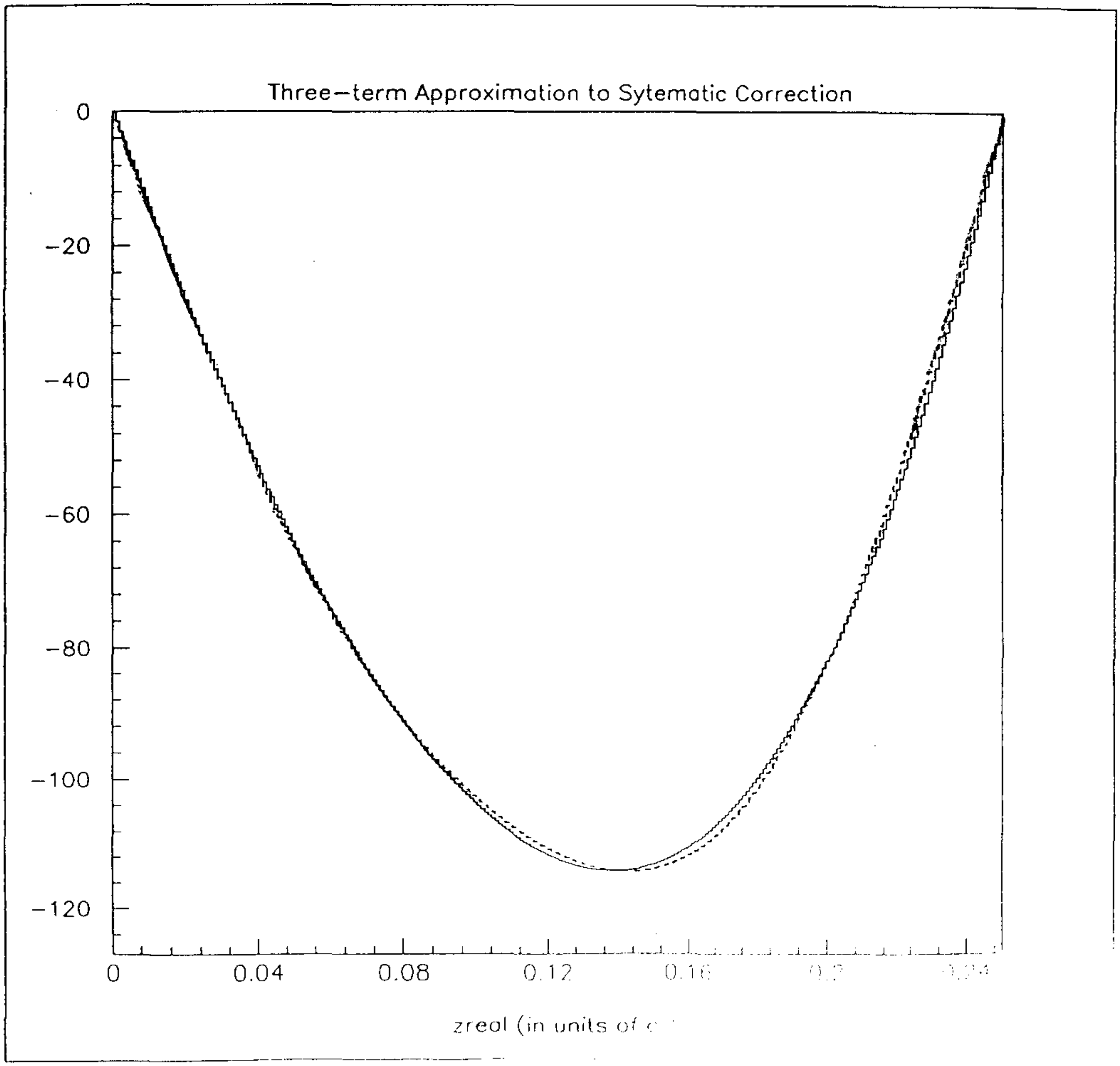
a.
Sum of pulseheights for 4 strips, three layers
3.3 kV, no overflows
3.3 kV
200
150
100
50
0
0
2000
4000
6000
8000
b
Sum of pulseheights for 4 strips, three layers
3.2 kV, no overflows
3.2 kV
160
140
120
100
80
60
40
20
0
0
2000
4000
6000
8000
c.
Sum of pulseheights for 4 strips, three layers
3.1 kV, no overflows
3.1 kV
250
200
150
100
50
0
0
2000
4000
6000
cnt

$$\Delta z = -117.07 \sin\left(\frac{2\pi z}{0.5\,\text{cm}}\right) + 9.07 \sin\left(\frac{4\pi z}{0.5\,\text{cm}}\right) - 4.85 \sin\left(\frac{6\pi z}{0.5\,\text{cm}}\right)$$

$$0 < z < 0.25\,\text{cm}$$

Fig. II.4.2

——— exact



The spatial resolution is obtained from the residuals of a straight-line fit to the corrected positions. Figs. II.4.3a and b show the residuals before (a) and after (b) the systematic corrections are applied.

The resolution averaged over $|\phi| = 6°$ is shown in Fig. II.4.4a as a function of the high voltage. As one can see, except at 3.1 kV and $|\phi| = 8°$, all resolutions are below 75 μm. The best resolution of 40 μm (See Fig. II.4.4b) is obtained with the highest voltage explored so far (3.3 kV) and at normal incidence (± 2°).

II.5 Conclusions

It is shown that a sizable (1.0 m x 0.5 m) CSC prototype, constructed with strip boards provided by industry and open profile chambers from SCARF, achieved a spatial resolution of the order of 40 - 60 μm. The internal alignment and single layer resolution surpassed the GEM specification by a significant margin.

The prototype confirmed experimentally that the mechanical tolerance requirement for the open profile chambers are significantly lower than those of the MWPC counterpart. The placement accuracy of the anode wires of our prototype, for example, is estimated to be no better than 200 μm.

The percentage variation in resolution is about 9.5 times the percentage variation in high voltage, considerably lower than that reported to date for the MWPC CSC's.

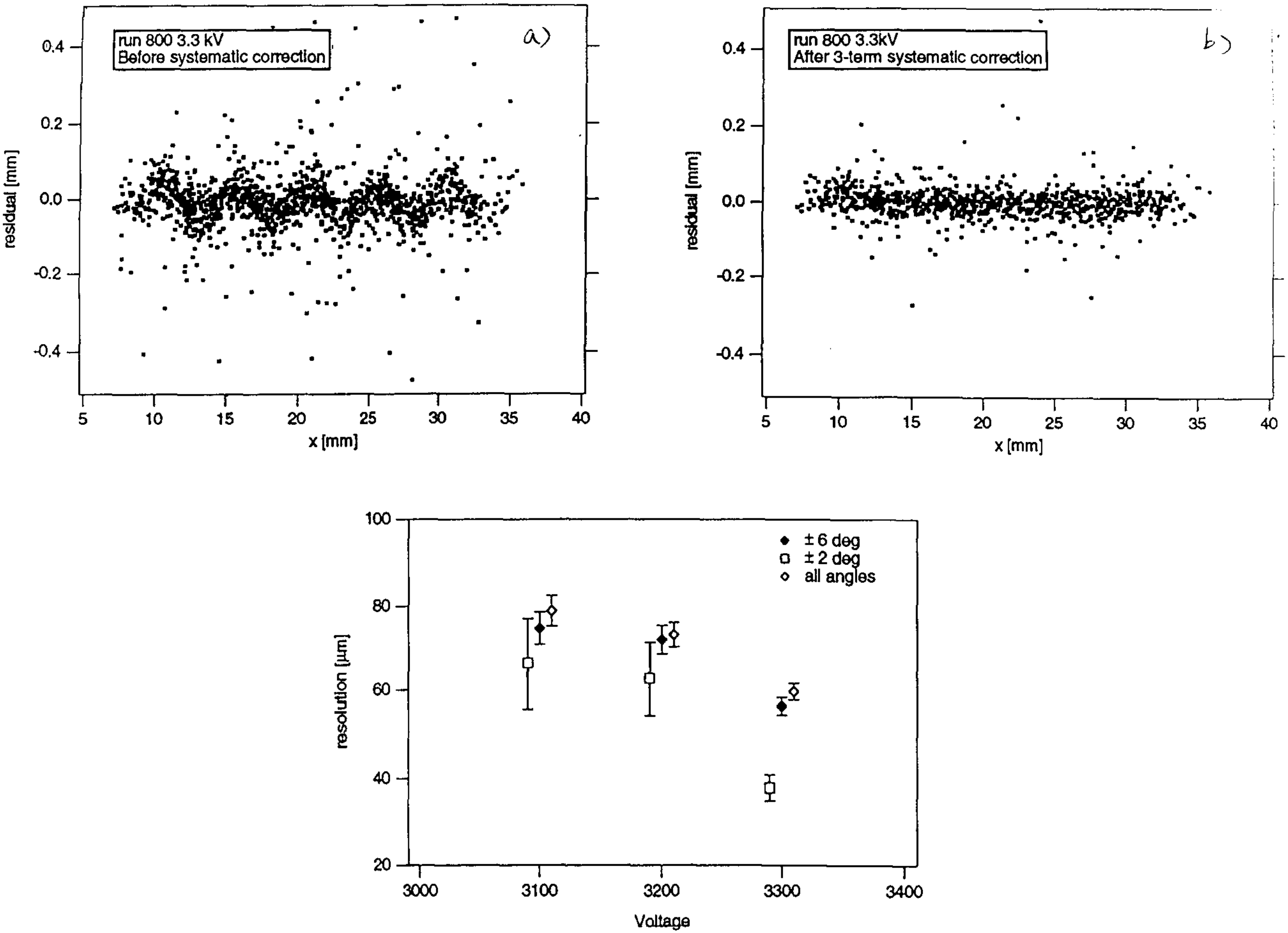
The operation of the prototype is stable and there is still ample room for optimization of most of the parameters.

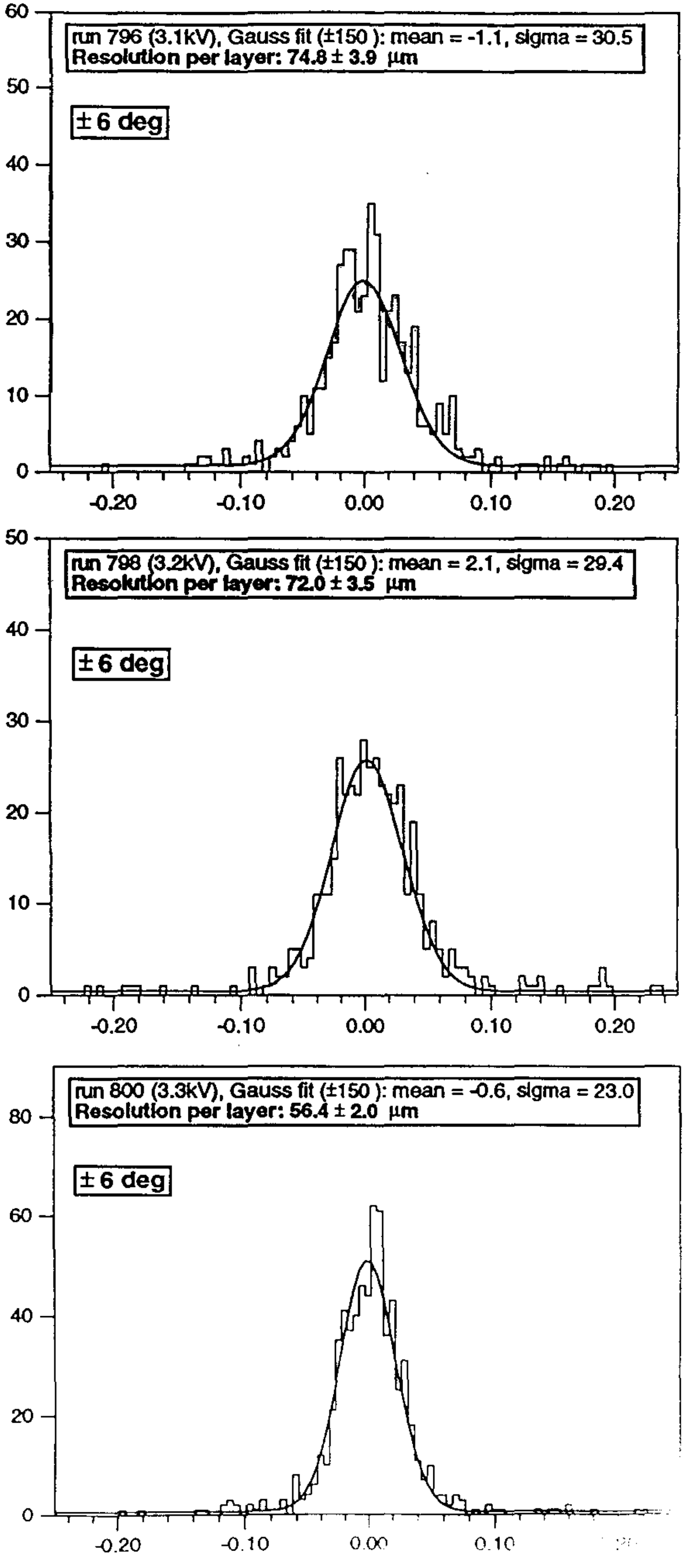
Construction of SPC full size prototype is recommended, and can be readily accomplished.

Future Studies

Many features of SPC geometry are still under study, including trigger efficiency, neutron efficiency, further HV studies, alternate gases, etc. In our judgment, a full size prototype should be built immediately.

Fig. II.4.3abc


run 800 3.3 kV
Before systematic correction
a)
residual [mm]
x [mm]
run 800 3.3kV
After 3-term systematic correction
b)
residual [mm]
x [mm]
± 6 deg
± 2 deg
all angles
resolution [μm]
Voltage



60
50
40
30
20
10
0
run 796 (3.1kV), Gauss fit (±150): mean = -1.1, sigma = 30.5
Resolution per layer: 74.8 ± 3.9 µm
± 6 deg
-0.20
-0.10
0.00
0.10
0.20
50
40
30
20
10
0
run 798 (3.2kV), Gauss fit (±150): mean = 2.1, sigma = 29.4
Resolution per layer: 72.0 ± 3.5 µm
± 6 deg
-0.20
-0.10
0.00
0.10
0.20
80
60
40
20
0
run 800 (3.3kV), Gauss fit (±150): mean = -0.6, sigma = 23.0
Resolution per layer: 56.4 ± 2.0 µm
± 6 deg
-0.20
-0.10
0.00
0.10

Fig. II.4.4a

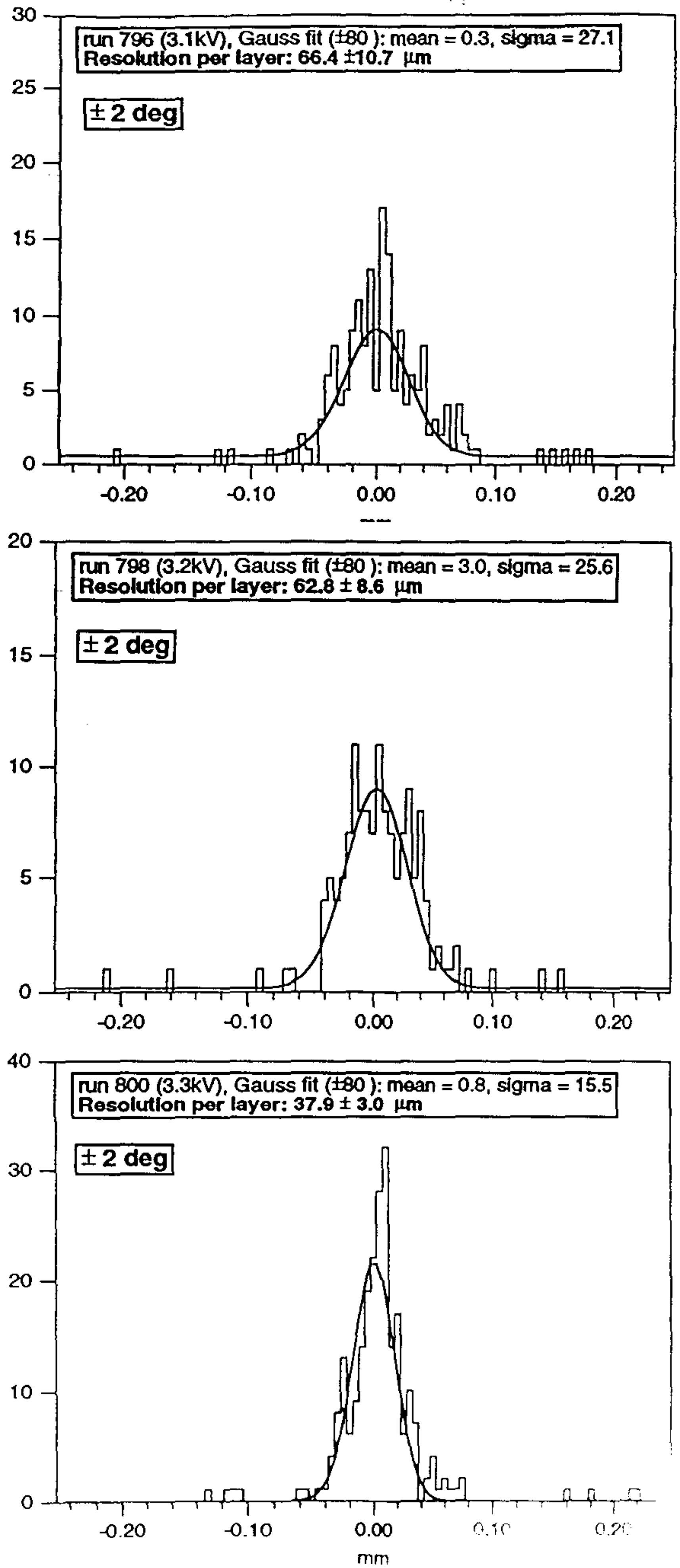

run 796 (3.1kV), Gauss fit (±80): mean = 0.3, sigma = 27.1
Resolution per layer: 66.4 ±10.7 μm
± 2 deg
30
25
20
15
10
5
0
-0.20
-0.10
0.00
0.10
0.20
run 798 (3.2kV), Gauss fit (±80): mean = 3.0, sigma = 25.6
Resolution per layer: 62.8 ± 8.6 μm
± 2 deg
20
15
10
5
0
-0.20
-0.10
0.00
0.10
0.20
run 800 (3.3kV), Gauss fit (±80): mean = 0.8, sigma = 15.5
Resolution per layer: 37.9 ± 3.0 μm
± 2 deg
40
30
20
10
0
-0.20
-0.10
0.00
mm

Fig. II.4.4b

Sec. III Costs

In this section, we estimate the costs of the proposed open profile geometry. In the construction, we propose to use commercially available parts for strips, proportional chambers, and hexcell. We do not propose new developments in these components, in this estimate. The assembly of the components into super layer segments is not assumed to be commercial. For that operation we estimate labor hours paralleling SCARF operations, and parts cost based upon the UH strip chamber prototype.

In order to be able to compare the cost estimates made here to cost reports provided on the MWPC geometry, at the GEM muon meeting of Jan. 19, 1993, *we assume, in this section only, an 8 4 4 geometry*, although like many others, we prefer an 8 6 6 geometry. We further assume 24 ϕ segments. In the outer layer, we assume two modules to cover the ϕ interval. In the region $\Theta_{min} \leq \Theta \leq 90°$, we assume 4 segments each in the middle and outer superlayers, and 2 in the inner layer. We further assume that super layers are constructed of modules 4 layers thick. We believe that these geometrical assumptions represent the assumptions made in the cost estimates of 1/19/93 for the MWPC geometry.

We will use the following terminology; A super layer is assembled from construction modules. In this cost estimate all modules are composed of 4 detector layers. Thus in the inner super layer there are two modules in each ϕ segment, one on top of the other (See Fig. III.1.1). In the outer super layer there are two modules, side by side.

Sec. III.1 Precision G10 Strips

We use the G10 cost estimate provided by MPC Inc., Lowell Mass, previously forwarded to GEM cost estimators. (See Appendix A) MPC also provided the strips for the UH prototype. The dimensions used in the 8 4 4, 24 segment geometry differ some what from the dimensions in the quote. In order to compute G10 costs, we scaled the quoted material in proportion to the area of G10 needed. The areas resulting from the assumed segmentation are given in Table III.1

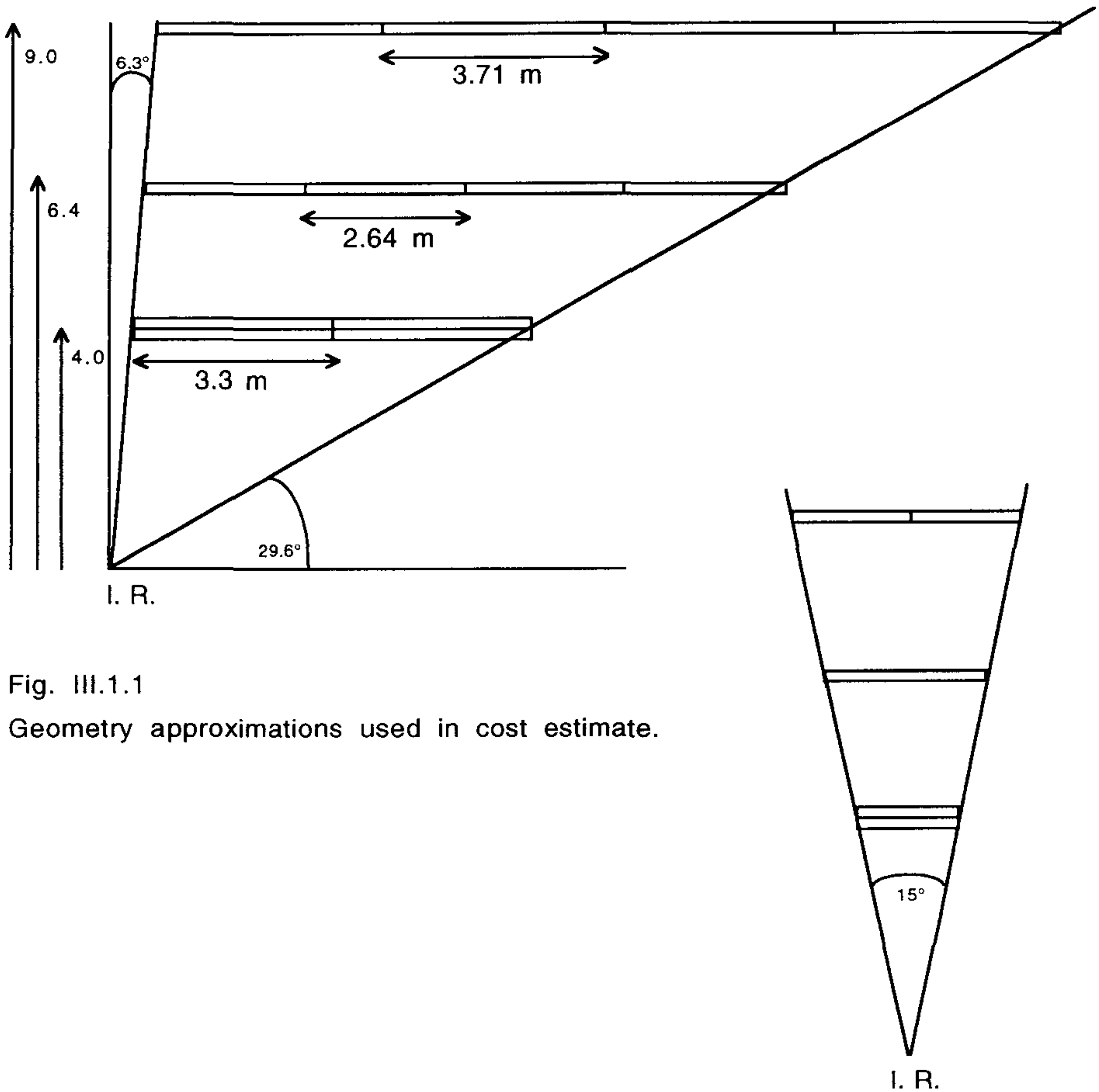


Fig. III.1.1
Geometry approximations used in cost estimate.

Table III.1.1 Areas of Detector Planes

Super Layer	Θ length (m)	φ length (m)	Area (m^2)
Inner	3.30*	1.05	3.46
Middle	2.64	1.68	4.42
Outer	3.71	1.18	4.36

The number of planes of each area is 4 times the number of modules.

Table III.1.2

Super Layer	φ segments	Θ segments	r segments	total # modules	# layers/mod.	total # layers
Inner	24	4	2	192	4	768
Middle	24	8	1	192	4	768
Outer	48	8	1	384	4	1,536

The G10 cost is the number of each type of layer (Table III.1.2 last column), times the area of each layer (Table III.1.1, last column) times the cost per m^2.

Table III.1.3

Super Layer	# of layers	area (m^2)	cost/m^2	cost per module
Inner	768	3.46	$306	$812k
Middle	768	4.42	$233	$791k
Outer	1,536	4.36	$225	$1,507k
		Total Strip Area 12,748 m^2		
		Total Precision Strip Cost $3,110k		

* The two Θ segments of the inner layer were taken to be of equal length, for simplicity.

There are some small additional set up, art work and shipping charges. We take the cost of precision G10 to be:

Total Precision G10 Strip Cost: $3,150 k

Sec. III.2 Cost of Proportional Chambers

For the purposes of estimating cost, we assume 8 anodes per chamber, with 1 cm pitch cells, 0.9 x 0.9 cm^2 in area, on a PVC base which is C coated. Such chambers have been built by research laboratories at Frascati, Dubna, Beijing, SCARF, and an MIT lab near FNAL. They are also sold commercially by Hodotector Corp., Houston, and by Pol Hi Tech Corp., Italy. The construction is well understood, and largely automated (See Sec. IV.1)

We have knowledge of costs, and previous commercial quotes, both by Pol Hi Tech and Hodotector. The cost estimate which appears below is based upon the lowest commercial quotes known to us, reduced by 10% for large quantity.

We count the number of chambers in one layer of one sub module by dividing "Θ length," from Table III.1.1 by 8.4 cm, and rounding down to an integral number. The 8.4 cm value is the overall chamber width including outer sheath, and tolerances. We then multiply by the number of layers (last column Table III.1.2). The length of each chamber is set equal to the "ϕ length,"

Table III.2.1

Super Layer	# 8 wire chambers per layer	# layers	total # 8 wire chambers	length of chamber	cost (est.) per chamber	cost of superlayer
Inner	39	768	29,952	1.047 m	$65.70	$1,968 k
Middle	31	768	23,808	1.675 m	$70.20	$1,671 k
Outer	44	1,536	67,584	1.178 m	$66.63	$4,503 k
					Total PC Cost	$6,163 k

Total Proportional Chamber Cost $6,163 k

* N.B.: If other considerations permit keeping the outer ϕ bin as a single bin, a considerable cost saving can be achieved by making one sub module in the ϕ direction in the outer layer. The price of a sealed proportional chambers varies very slowly with length, but is proportional to number of chambers. By designing for 1 ϕ unit in the outer layer, the number of 8 wire chambers in the outer layer is

reduced by 2, and the length is increased by 2. Wire instability is not a problem, since bridge supports are easy to install. In this geometry the cost per outer chamber is estimated at $74.70, and the total outer chamber cost is reduced to $2,524k , a cost reduction of $1,961 k.

III.3 Honeycomb Panels

We assume that panel cost is proportional to area, and we assume a cost of $100/m^2$. We assume that a 4 layer chamber requires 5 layers of panel, and an 8 layer chamber is built as 2 four layer chambers, and requires 10 layers of panel.

In Table III.3.1 the data are collected.

Table III.3.1

Super Layer	# layers of panel per mod.	area of panel (m^2)	# modules	Σ area (m^2)	Cost ($)
Inner	5	3.46	192	3,322	332.2 k
Middle	5	4.42	192	4,243	424.3 k
Outer	5	4.36	384	8,371	837.1 k
				Total Cost	$1,594 k

Total Hexcell Cost $1,594 k

Sec. III.4 Assembly of Sub Modules

We have estimated assembly time and cost, not including packing and shipping based upon (a) previous assemblies made at SCARF and CERN, and (b) shop time for the UH prototype operations.

We reviewed the assembly time with Coleman Johnson. The essentials of the assembly are that positioning the 8 wire chambers is uncritical. Anode-to-strip distances should be maintained to 200 μm. Strip position should be maintained to 50 μm. This latter tolerance is achieved by optical alignment.

The number of modules, from Table III.1.2, is 384 + 192 + 192 = 768.

We estimated 20 hours of assembly time per module, plus 12 hours of fiducial positioning, hole drilling, etc., for a total of 32 hours.

$50/hr x 32 hours/sub module = $1,600/sub mod.

768 sub modules at $1,600/module = $1,229 k

In addition, assembly bolts spaces, etc., add a cost of $138 k as in table 4.1

Total Assembly Labor and Small Parts = $1,367 k.

Table III.4.1

	# sub modules	# per sub module	total #	unit cost	Cost ($)
Bolts	768	4	3,072	$20	61.44 k
Spacers	768	2	1,536	$10	15.36 k
Al Plugs	768	16	12,288	$5	61.44 k

Sec. III.5 Totals

III.5.1 Totals

Cost of G10, Precision Strips	$3,150 k
Cost of Proportional Chambers	6,163 k
Cost of Hexcell	1,594 k
Cost of Assembly Labor (+) Small Parts	1,367 k
Total	$12,274 k

Conclusion:

Cost Estimate of 8 4 4 geometry, 24 ϕ segments: $12,274,000

Note: The cost of high voltage and gas connectors are not included in this cost estimate.

III.5.2 Comparison to MWPC Geometry

The cost listed above is to be compared to 3 columns on the cost estimate sheet of 1/15/93, titled "Muon Subsystem Cost Summary, Rev. 15." For MWPC these numbers appear as:

MWPC

Materials:		$14.552 million
Assembly:		13.378 million
Des. Gr. Allow:		10.055 million
	Total	$37.985 million

We note that the full contingency, $10.841 million, is 36.% of the total of direct estimates. We use this same percentage, applied to materials and assembly, in the SPC cost estimate. This results in:

SPC

Materials and Assembly		$12.274 million
36% contingency		3.682 million
	Total	$15.956 million

If these numbers are confirmed by the cost estimators, a saving of $22.029 million results from using the SPC geometry.

We make 3 further observations.

1. If the support frame geometry, ϕ segmentation, etc. permit building a single unit in the outer layer, per ϕ segment, a saving of $1.961 million results, as noted in Sec. III.2.

2. The labor involved in 20 hours of the estimated 32 assembly hours, is easily provided at $30/hour (at least in Houston that is the case) in place of the canonical $50 hours used in the estimate. If we are permitted to use such $30/hour labor, a cost reduction results of ($50-$30) x 20 hours/sub module x 768 modules = $307 k.

3. The SPC approach greatly reduces reliance on laboratory production, and replaces it with commercial production. We would be inclined to assign a significantly lower contingency percentage to SPC than to MWPC.

If (1) and (2) are permissible, a cost reduction of 1.30 x $2.268 million = $2.948 million results. Then the total SPC cost is then $13.008 million, a saving of $24.977 million, or about 65%.

Sec. IV. Technical Comparisons of SPC and MWPC

Sec. IV.1. Automated Production from Commercial Sources

The two major components required for strip detectors with separated profile chambers are produced by industry. Only the macro-assembly (See Fig. II.2) of these large components into the GEM superlayers need involve scientists and other costly personnel. We consider below the sources of (A) the active elements (proportional chambers in separated profiles) and (B) the strips. The third component, hexcell, is well known, and broadly used.

A. Active Elements

i. Assembly Steps

The active elements are proportional wire counters in separated profile chambers.

The method of assembly was developed by Iarocci in the early 1980s[1]. The following steps are required. (See Fig. IV.1.1).

a) The profiles are coated with Carbon DAG.

b) End wire supports, and/or electronics are inserted.

c) Bridges are inserted at whatever spacing is desired.

d) Wires are strung, and fixed at end supports.

e) Plastic from bridges is melted over anode wires to enclose them, and support them against electric or other instabilities, and sag.

f) The assembly is slipped into an enclosing "sheath."

g) End plugs are inserted into the sheath.

h) The assembly is sealed by melt sealing the sheath.

i) The assembly is leak tested.

j) The assembly is burned-in.

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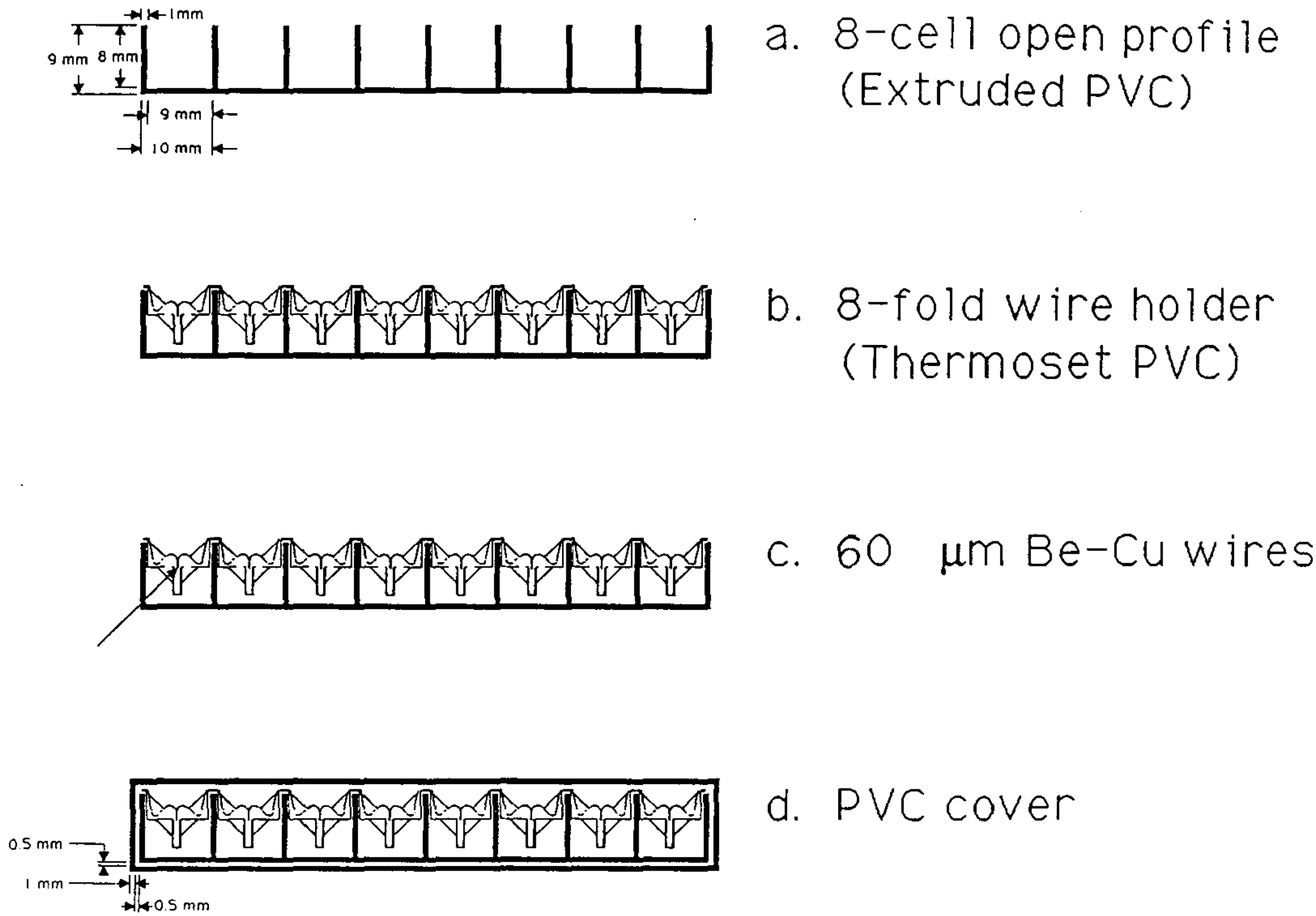
(1) E. Iarocci, Nuc. Instr. and Meth, 217, 30 (1983).

Fig. IV.1.1



STEPS IN STREAMER CHAMBER PRODUCTION

Iarocci-type chambers have been produced in large numbers with cell pitches of 3 cm, 1 cm, and 0.4 cm, on PVC, aluminum, or bakelite base. Smaller pitches are possible in the proportional mode (but not in the streamer mode).

ii. Automation

Using 1 cm pitch chambers, as an example (See Fig. IV.1.2), we now review the state of automation.

The most critical production steps are a, d, e, h, and i, above.

Step (a), DAG coating, was automated by Iarocci, advanced by Bindi Corp., and improved to essentially a fault free status by SCARF.

Step (d), wiring, was automated by Iarocci, very much improved by CERN, using a wholly different technique which was then further marginally improved at SCARF.

Step (e), bridge melting, was automated by Iarocci, but this method was abandoned, and a much improved method was developed by SCARF.

Step (h), chamber sealing, was semi automated by Bindi Corp., and fully automated at SCARF.

Step (i), leak testing, was semi-automated by SCARF.

Items b, c, f and g, the only steps not automated, are normally performed by unskilled labor.

Because of the inexpensive components and high degree of automation the sealed chambers are very cheap. Chambers 6.2 m long, with 8 cells of 1 cm (i.e., 1 cm x 8 cm x 6.2 m) have been produced in large quantities for as little as $80 per 8 anode chamber.

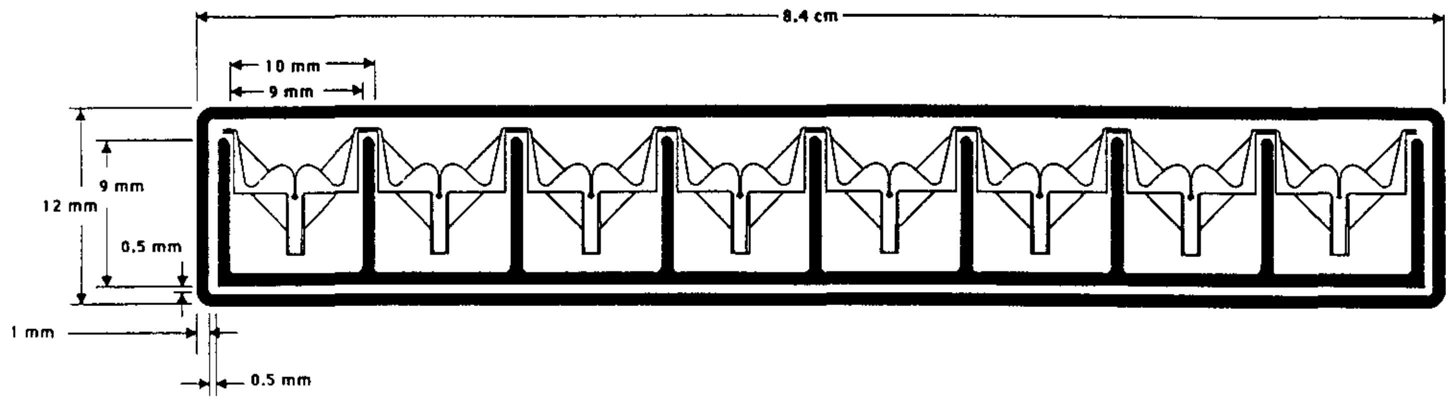
At present, such chambers are available commercially from 2 companies, Pol Hi Tech, of Aquila, Italy, and Hodotector Corp., of Houston, Texas. They also have been produced by several world laboratories including Frascati, Dubna, CERN, SCARF, Beijing, and an MIT plant at FNAL.

Initial delivery is commercially available in 6 weeks.

B. Strips

Strips may be machined or produced by photo etching to the accuracy required for strip chambers.

Fig. IV.1.2



We have sought out companies who do commercial photo etching. Our limited manpower precluded also seriously pursuing a machining source at the same time. The photo etching sources are quite satisfactory. However, machined precision strips may also be a practical solution. Cas Milner reports accurate strips by a printing method at NIKHEF[3].

A study of errors on photo etched strip prototype boards from MPC Corp. was performed, and reported to GEM by Lau. All necessary specifications were met on the 1.0 x 0.5 m^2 prototype, and no iterations with the manufacturer were required.

The same company, MPC Inc., has estimated the cost of larger strips in larger numbers. A recent cost estimate is given in Appendix A, and used in the cost estimate of Sec. III.

Initial delivery is available commercially in 10 weeks.

Strips included as an integral component in Hexcell is also being pursued by GEM. We note here that this structural variation, which may reduce costs or may increase them, is applicable to both the SPC and MWPC chamber technologies. Because, in SPC geometry the anode-strip distance is not critical, and 0.008" error is acceptable (See Sec. II), there is little gain to SPC construction in strips joined to hexcell, unless price is thereby reduced, or unless radiation length is deemed critical.

The cost of commercial proportional chambers, and commercial strips have gone into our cost estimates, made in Sec. III.

Sec. IV.2 Resolution Stability

From data reported at the 1/8/93 GEM muon meeting, a 50 Volt change in the high voltage of 2,600 Volts (i.e., a 1.92% change) caused a change in resolution from 76 μm to 104 μm in the MWPC prototype (i.e., 37% change in resolution).

In the open profile prototype, a 100 Volt change in the high voltage of 3,300 Volts, i.e., 3.03%, caused a change in resolution from 56 μm to 72 μm (i.e., 29%). Both sets of data were in the interval ± 6°.

Thus the voltage instability factors, f, where

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(3) V. Van de Graff et al., Nuc. Inst. and Meth.

$$f \equiv \frac{\Delta\sigma}{\sigma} \Big/ \frac{\Delta HV}{HV}$$ Eq. IV.4.1

for these prototypes were:

	SPC	MWPC
f	9.5	19.2

Sec. IV.3 Wire Stability, and Positioning Specification

Wire Stability

The limitation of the length of the unsupported anode wire in MWPC construction is easily solved in the case of open profile chambers.

The open profile chamber provides access to the wires, and also provides walls from which to support the anode, not easily available in MWPC designs.

The standard support used in open profile chambers, for the anode, is shown in Figs. IV.1.1 and IV.1.2. What is pictured there is a plastic "bridge." The bridge is supported by the open profile walls, and in turn supports the anode wire. Bridges may be placed as often as needed to provide stability for the anode.

The open profiles may be constructed, as noted earlier, of any material. C coated PVC, extruded Al, G10+Cu, bakelite, and sheet Al have been used. The bridge is made to have a snug straddle fit to any chosen open profile wall.

The bridge itself must be an insulator, to isolate the anode wire from the open profile ground. Plastic bridges are cheap and convenient, although any insulator is acceptable. The plastic bridges allow a simple low cost procedure for locking in the anode wire, in which the bridge is simply melted over the anode wire, and thereby locks in the anode. Automated machines to perform this task have been developed by Frascati and by SCARF.

Independent of the simplicity or complexity of the bridges, the fact that they can be used permits anode wires of any desired design length to be used then in the SPC geometry. The length of anode wire may then be set by engineering requirements, price considerations, or other detector or physics design criteria.

Anode Wire Positioning Specification

Anode wire movement due to sag or electrostatic instability can have an effect on the resolution, σ.

The SPC geometry is relatively insensitive to exact anode-strip distance. In the UH prototype a tolerance of $\pm$ 200 μm was allowed. The MWPC geometry appears to be very sensitive to the accuracy of anode-strip distance, and a tolerance of $\pm$ 20 μm has been quoted. Therefore construction constraints are relaxed in SPC geometry. One of the advantages of this is that it permits removal and replacement of bad wires, by replacing one 8 wire anode chamber in a simple operation. (See Sec. IV.5).

Sec. IV.4 The Wire Breakage Problem

One advantage of separated profile chambers is that they permit protection against wire breakage. Each wire is in a separate container e.g., 0.4 , or 1.0 cm wide. The wires may be fused to prevent HV shorts.

Estimation of wire breaking probability is trivial, but not easy. Broken wires are rare, and a large sample is required. Ideally, the sample involves the same wire material, diameter, and tension as that involved in the proposed chambers.

We follow, here, a less-than-purist path in order to guesstimate the severity of the wire breakage problem. We consider below evidence on breakage of 100 μm silver coated BeCu wire[5], which we believe provides qualitative evidence on gold coated W wires. The BeCu wire was used in separated profile streamer chambers.

The BeCu wires are mounted in the usual streamer geometry, supported approximately every 0.5 m, under a tension T = 296 gms.

Occasionally, during production wiring of the chambers, a wire will break. These breaks are not considered in the estimates given below, since they are logistically easy to handle. Also, during testing, before installation, a small number of broken wires are seen. These are not considered below because they also are not logistically troublesome.

After mounting and initial operation of the chambers, wire breakage is still observed. It is these breaks we consider, because in a detector with MWPC wiring these are logistically troublesome.

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(5) made by Little Falls Alloys Inc.

For example, for the SMC experiment at CERN, 1,000 4 m long chambers each with 8 anodes were shipped to CERN and re-burned in. The failure rate upon reconditioning, due to all causes, was 0.4%. World wide, a reburn-in loss rate of 25 - 35% is reported, and so these are reasonably described as "well made" chambers.

In one year of operation, 2 wire breaks occurred during running.

The total wire length involved for the 1,000 chambers, 4 m long, with 8 wires each, was 32,000 m, or about 20 miles of wire. Thus a breakage rate of about 1 per 10 miles of wire, was observed.

In order to convert the SMC experience qualitatively to GEM geometry, we approximate the barrel as 20 m long, and 8 m in radius, wound with a pitch of 0.3 cm, 18 layers deep. Eighteen layers then have about 6×10^6 m of wire $\approx$ 3,700 mi.

A breakage rate of 1 per 10 miles per year would result in 370 breaks/year in the above system.

If GEM barrel construction is modular, with ~1,000 modules, having typically 6 protected layers (and if the above numbers based on BeCu apply also to W) then about 6% of the GEM barrel counter single layers, and about 31% of GEM modules will have one or more broken wires after 1 yr.

Our model of fine wires is that they have occasional deformities caused by an impurity deposit in the melt being pulled through the die with the wire. If this model is correct, the experience with large lengths of W wire will parallel that with BeCu wire.

Sec. IV.5. <u>Repair</u>

An open profile chamber is a sealed unit. In the UH prototype design, an individual chamber may be removed from the assembly, and replaced by a like unit.

In the SMC experiment at CERN, for example open profile streamer mode chambers are used in a high rate environment (5×10^3 counts/cm^2/sec). About 20 of these chambers have been replaced in two years.

Such repair, when done on a super layer, may provide a significant cost savings. Instead of replacing a total superplane sub-unit (costing several thousand dollars), or a layer, or even repairing such a unit by delicate operations involving expensive personnel, the repair can be reduced to the removal and reinsertion of a unit costing about typically \$70. The operation can be done with entry level personnel.

Sec. IV.6 <u>Neutrons</u>

The Houston chamber has not yet been tested for neutron efficiency, in tests such as done by Osborn. These tests must be done. Until the measurement is done, we will use ballpark estimates of the neutron efficiency, ε_n.

For the purpose of a ballpark estimate, we note that Lou Osborn used an Al wall chamber with 2.5 cm of gas. He measured $\varepsilon_n \approx 0.5\%$. Extrapolating to zero gas, he found the efficiency of the empty chamber (wall) to be, $\varepsilon_w \approx 0.15\%$.

Attributing $\varepsilon_n - \varepsilon_w$ to the gas we find the efficiency per mm of gas

$$\varepsilon_g = 0.014\%/\text{mm gas}$$

In this discussion we shall assume the same gas is used in all cases, which will not be true, but allows us to approximate.

What neutron efficiency, ε_n, do we expect for the proposed separated profile chambers?

If they are made of Al on a 1 cm pitch, with 9 mm of gas volume, we expect a gas efficiency $\varepsilon_g = 9 \times 0.014\% = 0.126\%$. If this Al gets dirty, as in Osborn's case, we expect $\varepsilon_w = 0.15\%$. Thus we expect

$$\varepsilon_{n,Al} = 0.28\%$$

If the separated profile chambers are made of PVC with a carbon DAG coat, <u>and</u> the thickness of the DAG coat exceeds the recoil proton range, the gas signal expected is about the same as that from a gap of 9 mm in an Al chamber. The experience of Osborn leads us to expect dirt effects to add as they did in Al (ultimately the dirt is deposited from the gas). Thus we expect

$$\varepsilon_{n,c} \approx 0.28\%.$$

We conclude that the n efficiency for carbon coated PVC will be below that measured by Osborn, if the proton recoils from the hydrogenous material does not penetrate the C coating..

Effect of Carbon Coating on Hydrogenous Chambers

The neutron spectrum falls by over two orders of magnitude for $E_n \geq 0.1$ MeV. The maximum recoil proton energy for this neutron energy is 0.1 MeV. The range of 0.1 MeV protons is about 0.4 mg/cm^2[(6)]. For carbon coating ($\rho \sim 2.26$), a thickness of 1.77 μm has 0.4 mg/cm^2. The coating thickness of the UH prototype is estimated to be 5 μm.

From the above we conclude that the effect of the n,p interaction in the plastic, on the n efficiency of the proposed separated profile chambers, should be negligible, even if the chambers are manufactured on a PVC base.

The efficiency expected for the MWPC chamber, argued as above, is 5 x 0.0149/mm for the gas, and 0.15% for the hydrogenous "dirt," for a total of 0.22%.

We note once more that the above estimates and arguments are not intended to replace a proper measurement of the neutron efficiency.

Sec. IV.7 Losses in Shipping

During the period in which separated profile manufacturing was being debugged, and automation was being developed, world wide experiences on shipping was that losses were significant.

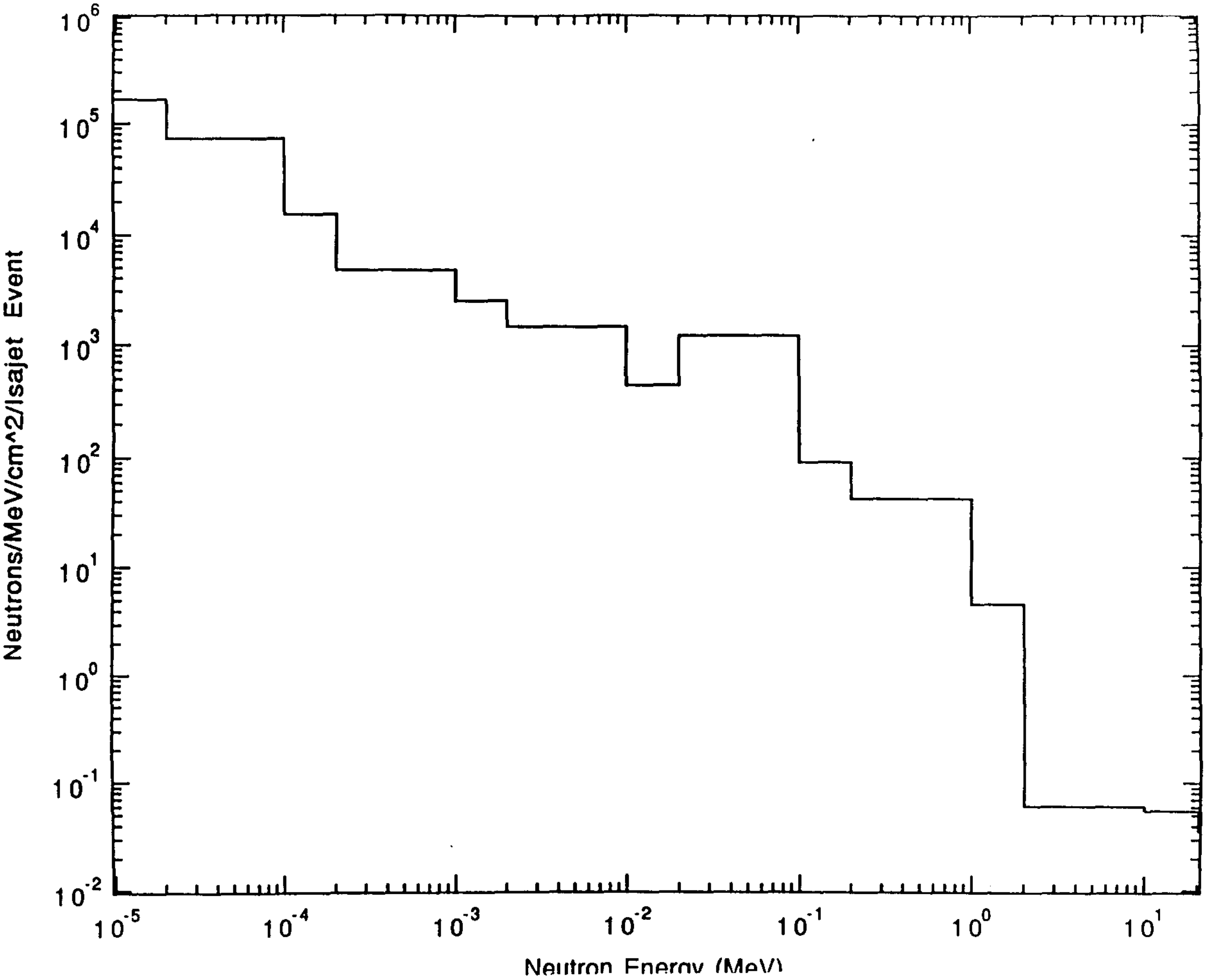
As part of the automation procedure at SCARF, shipping practices were developed. These include such things as pressure release to protect against large barometric changes, studies of resonant frequencies of anode wires, packing procedures, and container development.

"Drop Tests" were also performed involving about 100 sealed 8 anode wire chambers, 6.2 m long. These were dropped, typically from heights of 3 feet, on their edges, flat sides, and corners.

The stability for shipment of the resulting separated profile sealed 8 anode wire units was most carefully measured in a shipment of 1,000 chambers from Houston to CERN. After testing at Houston, the chambers were prepared for shipment using gas connections which permitted variation of pressure in the event

(6) Closerly related numbers are in H. Bethe, BNL T7, 1947.

Fig. IV.6.1



of barometric pressure changes, packed, moved by fork lift into standard modular shipping containers, moved by truck to the port, loaded on the ship, unloaded in Europe, moved by truck to CERN, unpacked, slipped into their support modules for the SMC experiment, hoisted by Crane into the experiment, flushed and re-burned in.

The total losses were 0.4% due to the cumulative effect of all of the above.

Based on this data we believe that no significant losses will be suffered in transit by the proposed separated profile chambers.

Sec. IV.8 Lifetime

Let us assume that the proportional mode results in a charge collection of 0.5×10^{-12} coulombs.

The life time for chambers with 20 μm anodes, and with no protection against aging (such as water vapor) is generally found to be ~ 1 coulomb per cm of anode wire.

One expects the life time to depend on deposits *per unit area* of cathode. Thus a 44.5 μm anode would be expected to survive 2.2 Coulombs of collected charge.

At 0.5 pc per pulse this corresponds to 4.4×10^{12} pulses.

At a count rate of 5×10^{3}/sec cm^2 (1.58×10^{11}/year) one expects 29 years of operation before aging is a problem. If highly ionizing neutron recoils account for most of the pulses, lifetime may be shortened by a factor of 10.

For the MWPC geometry, there are three times as many anodes, of diameter 20 μm. The gas path length for ion formation is a factor 1.1 to 1.5 smaller. The lifetime for such a geometry will be longer by a factor, f

$$f = \text{relative \# anodes} \times \text{relative ionization path/relative anode diameter}$$
$$= 3 \times 1.3/2.2 = 1.77.$$

Thus the MWPC lifetime is expected to be 51 years.

Both life times can be shortened if the dominant counts are large pulse height events, such as recoil protons. However, the pulse height is limited by recombination in the limited proportional region. We need to quantify the pulse height limit.

We find the behavior of the SPC, and the cost estimates, very encouraging. We continue to work on the several aspects mentioned earlier: trigger efficiency, neutron efficiency, further study of HV behavior, varying gas, etc. We believe that a full scale SPC should be built at this time.

Appendix A

MPC, INC
Microwave Printed Circuitry
81 Old Ferry Road
Lowell, MA 01854
Phone: 508-452-9061 Fax: 508-441-0004

QUOTATION

Company: Institute for Beam Particle Dynamics
University of Houston

Attn: Kwong Lau Date: 12/17/92

PART NUMBER	QUANTITY	UNIT PRICE	NRE
Type A Board (size to be 3152 mm x 370 mm)	1024	$357.06	$525.00
Type B Board (size to be 3028 mm x 370 mm)	1024	357.06	525.00
Type C Board (size to be 2515 mm x 660 mm)	2048	387.02	575.00
Type D Board (size to be 3506 mm x 480 mm)	4096	378.04	575.00

Due to processing size restrictions, boards will be supplied in the sizes given above.

MPC to supply material.
Artwork to be supplied by the Institute as 1:1 positives.
Delivery: Initial delivery - 10 weeks ARO and artwork
Delivery rate to be mutually agreed upon.
Terms: 1-10, N30 F.O.B.: Lowell, MA
Quotation is budgetary pending review of final drawings and requirements.

If you need additional information, please contact the undersigned.

Best Regards,

Bob Deitz