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SDC
SOLENOIDAL DETECTOR NOTES

TRACKING MUONS AT SSC

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University of Washington
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The scale of muon detectors of SSC experiments is unprecedented. As described in the EoI, the total area of the three SDC muon tracking stations is about $6,500m^2$ with each station containing 8 to 10 layers of drift tubes. The total number of sense wires is ~110,000 and the maximum chamber length is 8.5 meters. The design goal of measurement precision for each muon tracking station is 250μ which is extremely difficult to achieve for such a large system.

Two different types of muon drift chambers are used in large high energy physics experiments in the past. They differ from both mechanical structural design and the drift cell design.

1 Closed Cell Drift Tubes

1.1 The Simplest Drift Tube

The simplest drift tube has a single sense enclosed by a wall of circular, square or rectangular cross section. As shown in fig. 1a and fig. 1b for square and rectangular tubes, electric field has 1/r behavior over most of the drift volume. This kind of tubes can be operated either in streamer mode or proportional mode. They have been used in many experiments because its simplicity.

- ZEUS barrel and rear muon detectors[1] (fig. 2) use square drift tubes of $1cm \times 1cm$ cross section. Sense wires are supported every 45cm over a maximum length of 10 meters. Thick aluminium honey comb plates provide necessary mechanical support. These tubes are operated in streamer mode. Two dimensional coordinates are obtained by analog strips perpendicular to the wire and by the drift time measurements by TDC's. The bench test resolution for the coordinate along the wire direction is 150μ. The resolution in the drift direction is, however, much worse. 30% argon and 70% of isobutane are used as chamber gas. The scale of ZEUS muon detectors is very large. The total number of readout channels is about 100,000.

  The design of the EMPACT muon tracking chamber is very similar to the ZEUS muon detector. The EMPACT system are much bigger. They have over 500,000 tubes and the tube cross section is larger.

- VENUS muon drift chambers are made from rectangular drift tubes[2] which have a cross section of $7cm \times 5cm$. (fig. 3) The length of these tubes is 7.6m. The resolution obtained by bench tests using cosmic ray muons is 1.3mm. P10 gas (90% argon and 10% CH_4) is used in their tests.

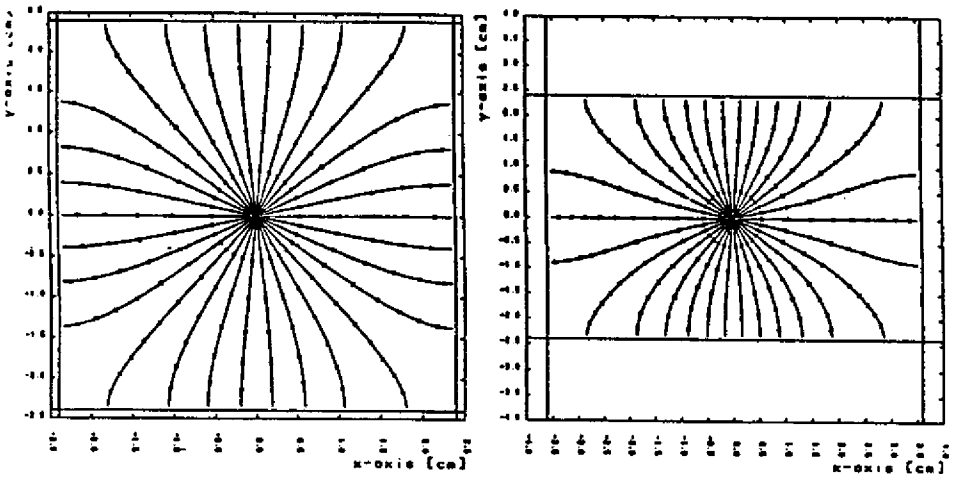


Fig. 1a and fig. 1b. Electrical field lines and isochrones in a square cell and a rectangular cell.

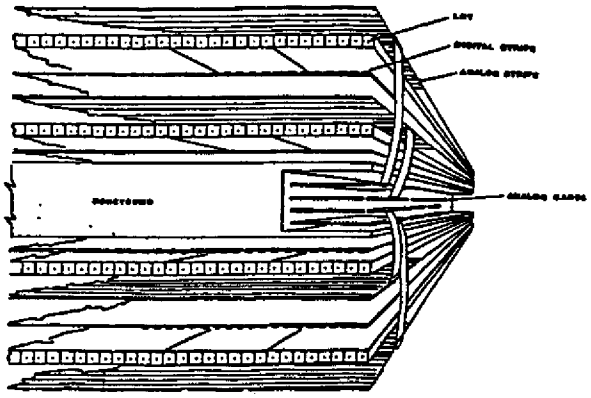


Fig. 2. The ZEUS barrel and rear muon detector.

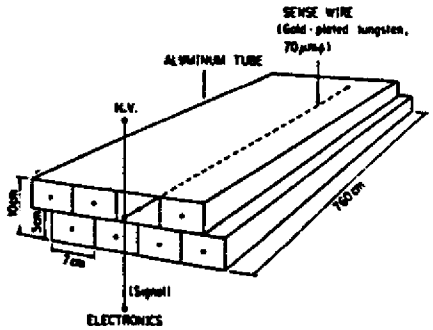


Fig. 3. The VENUS muon detector.

The proportional drift tubes used in a neutrino oscillation experiment at LAMPF is another example of the application of rectangular tubes.[3] The cross section of their tubes is 3.8 ×7.6cm and tubes are 3.7m long. These tubes are made from laminated Kraft paper.

- The MAC muon detector [4] is made from 10cm diameter cylindrical aluminium tubes. Their muon system do not require to have high momentum resolution because of the multiple scattering of muons at their energy range.

  The D0 SAMUS (small angle muon detector)[5] is made from 6,000 3cm diameter cylindrical drift tubes. The length of tubes are 0.2m - 3.8m long. The position resolution is 300μ measured in a muon test beam using pure CH_4.

There are serious problems for such type of drift tubes. The drift velocity in such simple tubes are very nonlinear due to the $1/r$ behavior of the electric field. In addition, the field near the tube wall is normally very low for large tubes. In order to obtain adequate drift speed, the VENUS system uses P10 gas which has drift velocity peaked at 100V-200V/cm. Their position resolution is rather poor because the drift speed of P10 gas strongly depends on the drift field. As we will see in the following discussion, these problems become less severe if field shaping electrodes are introduced.

1.2 MIT-Harvard Drift Chamber

The first large muon drift chamber design for a large collider experiment can be traced back to 1975[6]. Such kind of design has become a standard for muon chambers since it was successfully used by Mark-J experiment.

The size of the Mark-J chamber modules is quite large, $5.5m \times 5.5m$. A typical drift cell is shown in fig. 4a. The cell is closed by two I-profile beams which are held at negative high voltage. These I-beams, insulated from the grounded chamber covers, provide both mechanical strength and field shaping. The sense wire is normally at positive high voltage. The electrical field line flow inside a such cell is shown in fig. 4b. The chamber mechanical structure is shown in fig. 4c.

Although mechanically very simple, the electric field in such kind of drift cells is far from being uniform resulting non-linear drift time and drift distance relations especially for inclined tracks. In fig. 5, the drift field, drift time and distance relation of two different kind of drift cells are given for comparison. The left side is the MIT/Harvard cell and the right side is a drift cell with many field shaping wires. The gas mixture used in these measurements is 78% argon and 22% isobutane which is reasonably saturated above $E_d > 500V/cm$. The resolution of the Mark-J muon system is $600\mu m$.

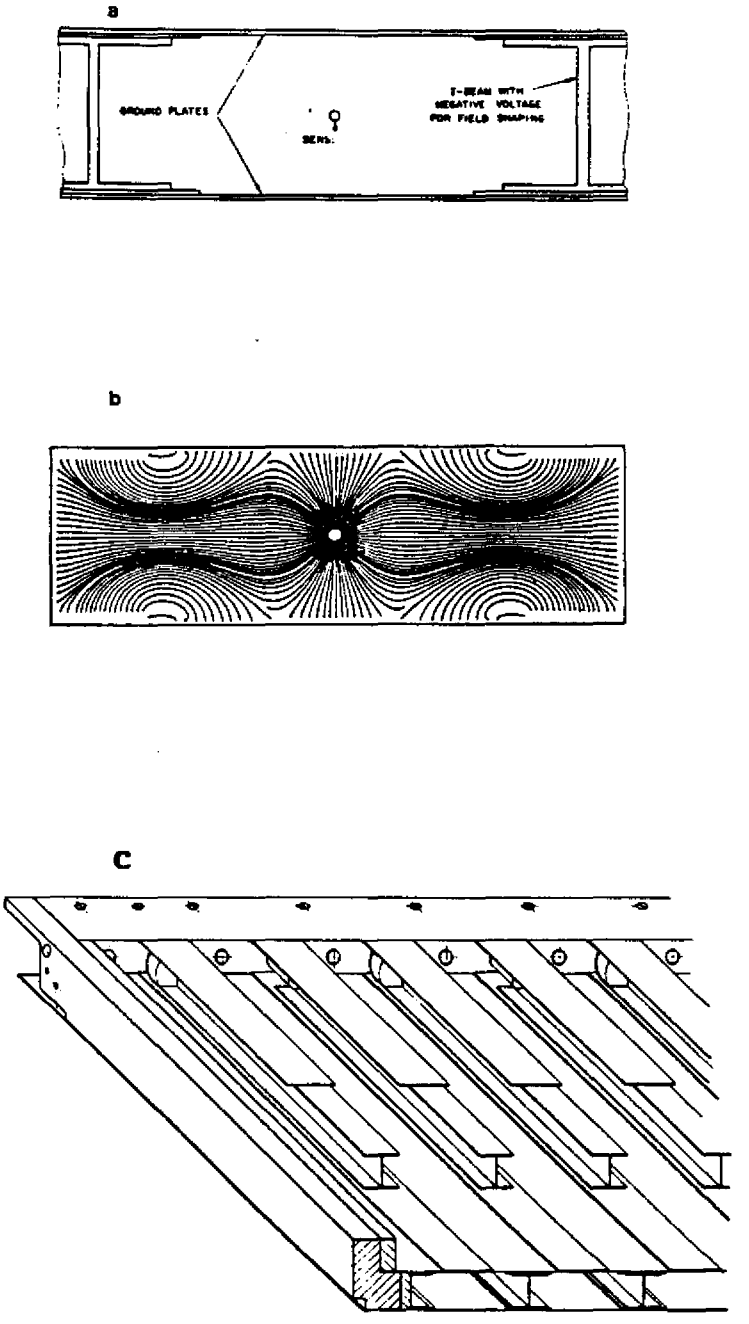


Fig. 4. a. The cross-section of a standard MIT/Harvard drift chamber cell.
b. The electrical field line flow inside a such cell.
c. Mechanical structure of the L3 Z-chamber.

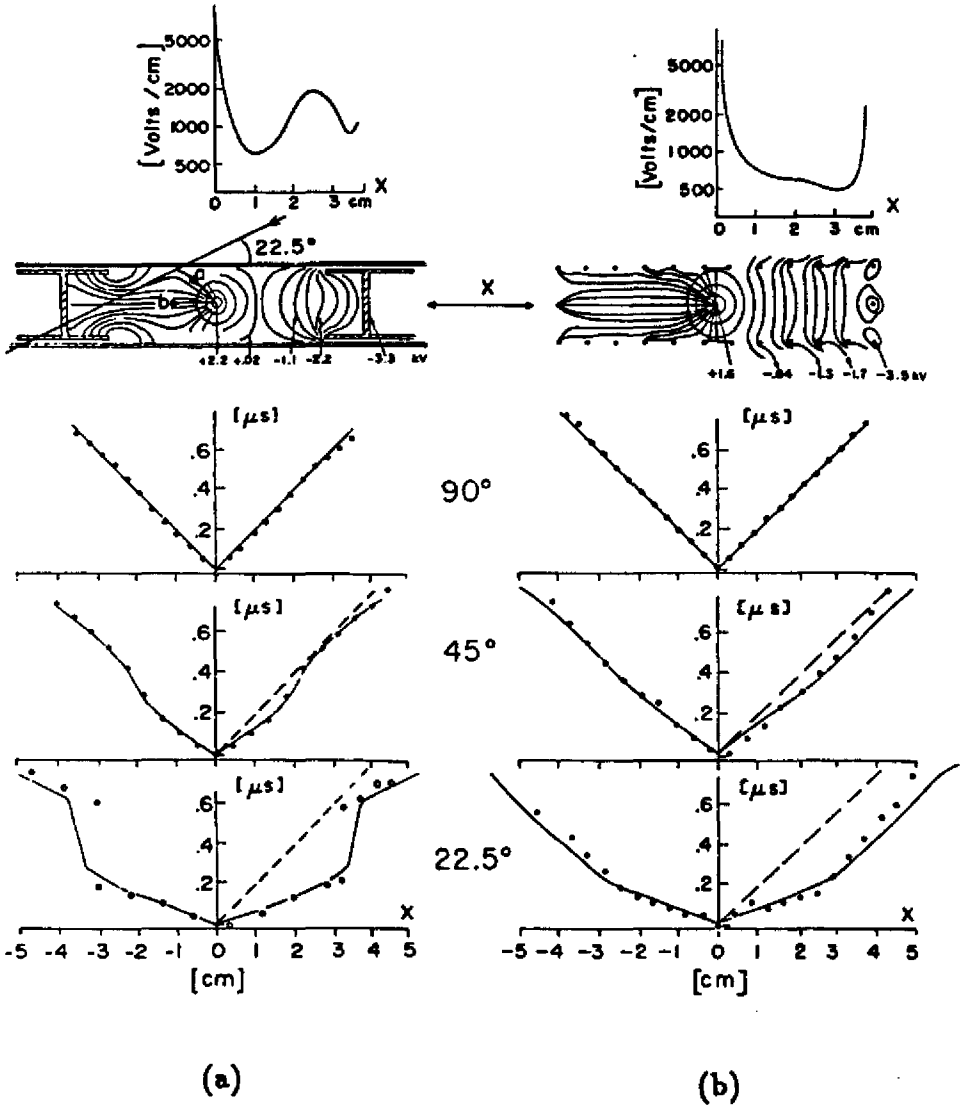


Fig. 5. (a) From the top to the bottom: Electrical field along x-axis; right: equipotential lines, left: electrical field lines; liniarity for 90° tracks; liniarity for 45° inclined tracks; liniarity fro 22.5° inclined tracks.

(b) Same for a chamber with many field shaping wires.

A 3cm × 9.2cm cell was chosen for the L3 Z-chamber.[7] The bench test resolution of this chamber using P10 (90% argon and 10% methane) gas is $\sim 1mm$ assuming constant drift velocity and $< 400\mu m$ after corrections.

In fig. 6a, the cross section of a CDF drift cell is given[8]. Their cell is relatively small, only $2.7cm \times 6.4cm$. Although the drift field is poor as shown in fig. 6b, the achieved resolution is pretty good, $250\mu m$ as measured using cosmic ray muons. Saturated chamber gas was used and the chamber is operated in limited streamer mode.

In this type of cells, the drift field uniformity is determined by the aspect ratio, the ratio of cell height over cell width. It is possible to make the field uniformity exceptionally good by optimizing this ratio. The issue of drift cell design optimization will be discussed in section four of this paper.

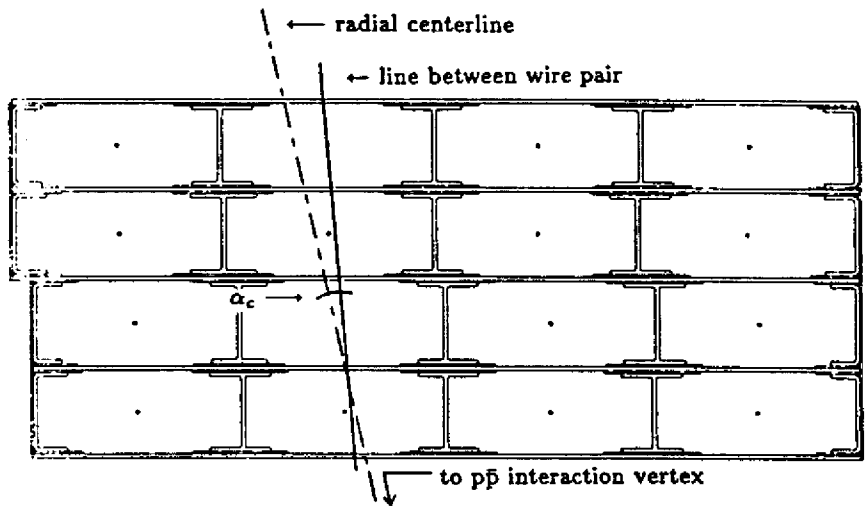


Fig. 6a. Cross section of a single muon chamber, showing the tilt angle α_c of the chamber relative to a radius extending from the pp̄ interaction vertex. α_c must be known to make a p_t measurement.

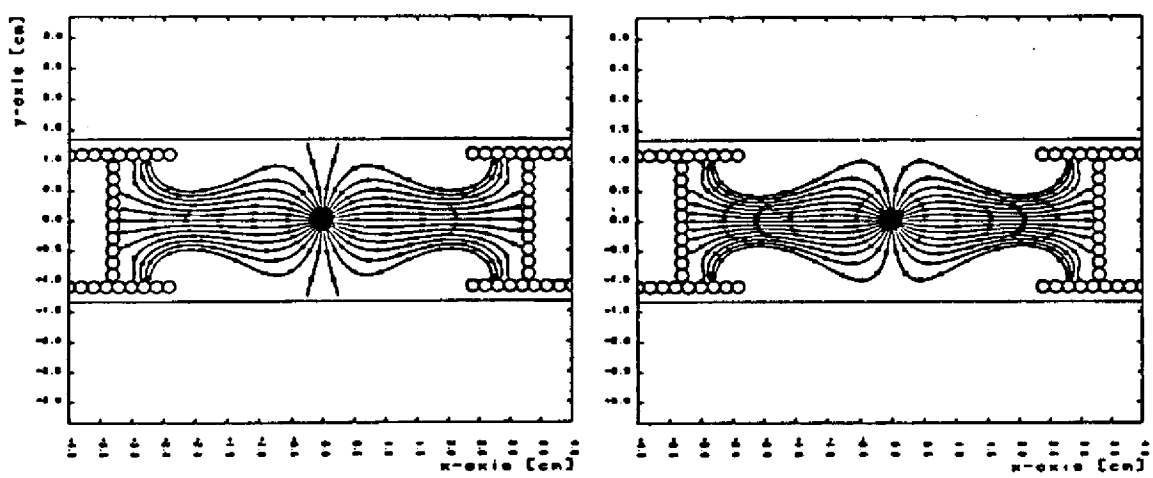
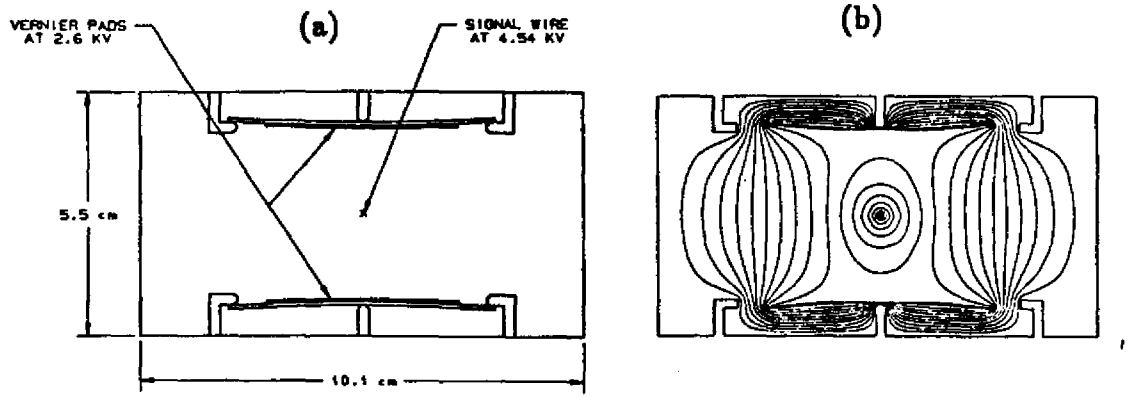


Fig. 6b Electrical field line flow in a CDF muon chamber cell.
Left: Ar/Ethane streamer mode; Right: Ar/CO_2 proportional mode.

1.3 D0 Drift Tube

The D0 muon drift chambers[9] are made of extruded aluminium tubes.(fig. 7a). Although they are mechanically different, the electrode configuration of the D0 tube is essentially the same as the MIT/Harvard drift tubes. The rectangular aluminium tube is held at ground and the sense wire is at positive high voltage. Two field shaping electrodes (also used to readout coordinates along sense wires), one on top and one underneath of a sense wire, are held at ~2kV below the sense wire voltage. Good field uniformity is achieved by choosing relatively large aspect ratio. Their cell height is 5.5cm and the width is 10cm. The drift field is reasonably well behaved along the electron drift path(fig. 7b).

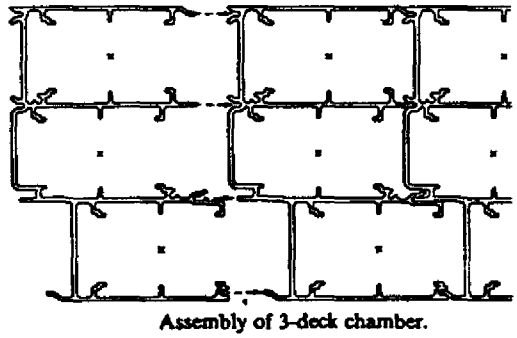
The gas used is a mixture of 90% argon and 10% CO_2.



Cross section of a wide angle PDT cell and its coordinate system.

Electrostatic equipotential lines of the 4 in. PDT cell signal wire at +5 kV, and Vernier pads at +2 kV.

(c)



Assembly of 3-deck chamber.

Fig.7. The D0 muon chamber.

1.4 Long Drift Distance Tubes

The UA-1 drift tube [10] is also made of extruded aluminium tubes. Their tubes have much more complicated structure. The cell cross section is shown in fig. 8a. There is a 3cm diameter cylindrical profile around the sense wire inside the $15cm \times 4.5cm$ extruded rectangular tube. Compared to the MIT/Harvard tubes, one more potential level (four electrodes) is added. This is necessary because of the relatively long drift distance of 7cm and small cell height of 3cm.

One can see in fig. 8b that although the drift lines are nicely confined within a narrow band, the drift field varies from 0.5kV/cm to 3kV/cm corresponding to a drift velocity change of only 3% using a well saturated argon/ethane gas mixture.

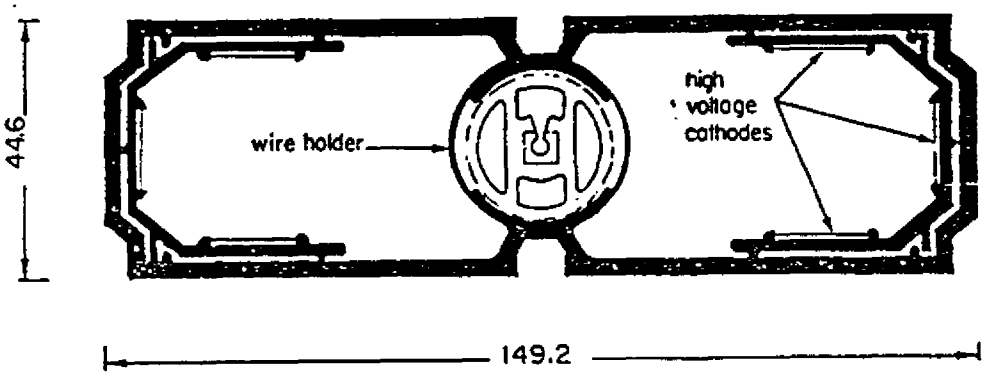
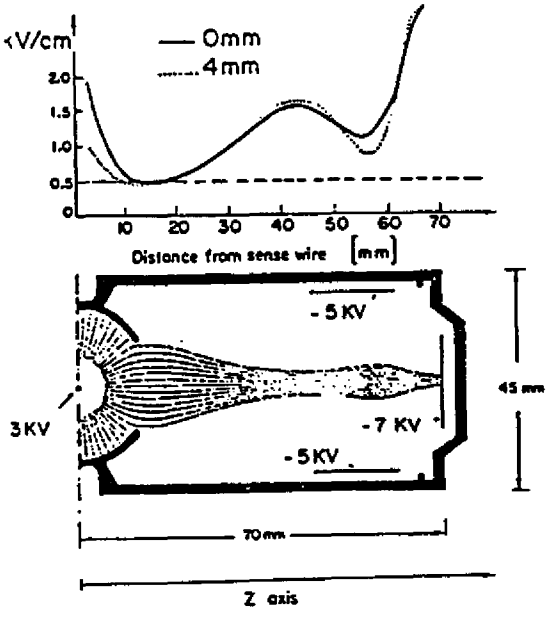


Fig. 8a. Cross-section of the extruded aluminium profile. Inserted are the PVC-U-profiles with the copper electrodes and the wire holder fixed in the center of the collimating electrode.

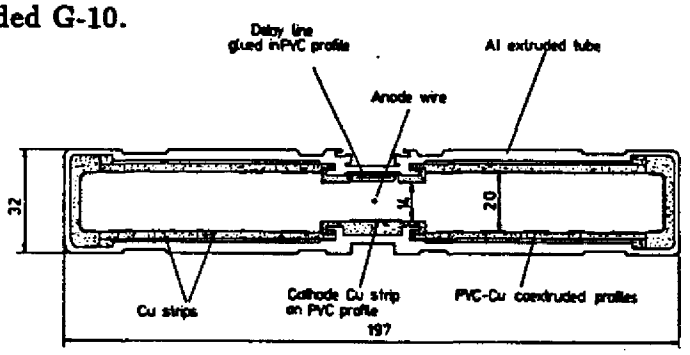


8b. Flow of the electrical field lines to the sense wire and the field strength at 0 and 4 mm distance from the z-axis. Three field shaping electrodes are sufficient to obtain a field strength above 0.5 kV cm^{-1}, the lower limit for electron drift velocity saturation in an argon/ethane (40%, 60%) mixture.

For even longer drift distance, one has to have more shaping electrodes. The DELPHI forward muon drift chamber[11] use 24 electrodes (6 potentials) in a $2cm \times 18cm$ drift tube. (fig. 9) These electrodes are constructed from PVC-Cu coextruded profiles inserted inside a extruded aluminium tube. They use 50/50 argon/isobutane gas mixture and chambers are operated in streamer mode. The intrinsic resolution of these chambers is $< 1mm$ measured using a test beam and cosmic ray muons.

The cell electrical design of the muon drift tubes for the CDF upgrade (central region) being built at Harvard and UIC is almost identical as the DELPHI tube. They have 2cm × 10cm cells. Tubes are made from extruded plastic with inserted electrodes made from cladded G-10.

Fig. 9.



Transverse cut of an individual drift chamber, unit detector cell of the DELPHI end-cap muon identifiers (units in mm).

Muon chambers in JADE experiment have 15cm long drift distance[12]. The drift cell cross section is $30cm \times 2cm$ (fig. 10). Each cell has 15 potential levels maintained by 60 field shaping electrodes which are connected to resistor chains of 10 M Ω resistors. A chamber cell is constructed from two sheets of copper-coated printed circuits board, separated at each long edge by U-shaped aluminium extrusions. The chamber gas is 90% argon and 10% ethane which is not saturated. The resolution is ~1mm.

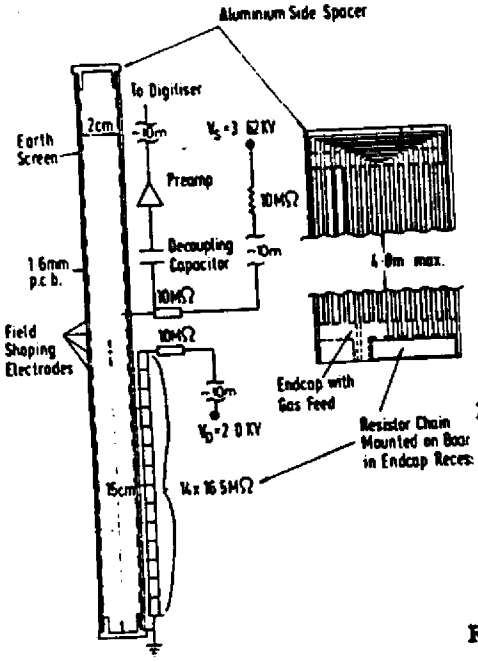


Fig. 10a Mechanical and high voltage details of a drift chamber module.

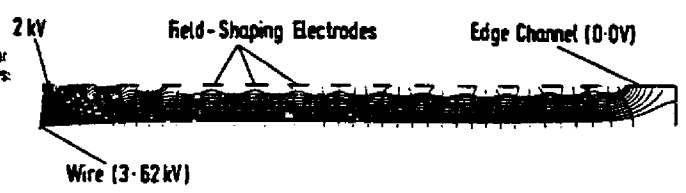


Fig. 10b. Simulation of field lines and equipotentials in a Jade muon chamber assuming optimal static charge on the insulating surfaces.

1.5 Contineous Field Shaping

Shaping the drift field without using metal electrodes has been an interesting subject. Very simple drift cells with good field uniformity can be made this way. Applying conductive paint (graphite) on the plastic tube inner wall was a conventional approach[13] but has never very been successful due to the difficulty of obtaining uniform coating and proper surface resistivity. Muon chambers made from insulating plates have been tried.[14] The field shaping is achieved by positive charge deposited on the inner surface of the chamber.

1.6 Summary

Drift field uniformity is a crucial factor for achieving good postion resolution. As discussed above, in order to achieve uniform drift field, some groups have designed drift cells with many field shaping electrodes. On the other hand, many groups have been focused on finding a simple way of obtaining acceptable drift field using a minimum number of field shaping electrodes in order to avoid high cost and problems associated with the complexity of handling many different high voltages.

Low cost and large scale construction is another driven factors in muon tracking chamber designs. Different groups have take different approach in this respect.

A summary of muon detector parameters in some important high energy physics experiments which use closed cell drift chambers are summarize in the following table.

Table 1. Parameters of Muon Detectors

Detector	Cell Size cm	Length m	Ch.	Area m^2	Gas	Resolution mm
Mark-J	6×2	5.5			Ar/C_4H_{10}	0.6
L3 Z-chamber	9.2×3	2.2	5,568	1,000	P9	1.2(0.5)
UA-1	14×4.5	4-6	5,200	500	Ar/C_2H_6	0.25-1
CDF Central	6.4×2.7	2.3			Ar/C_2H_6	0.25
Jade Central	30×2	3.5-4.8	618	800	P10	1
DELPHI	20×2	4.3		80	Ar/C_4H_{10}	(1)
D0 Central	10×5.5	< 5.8	16,618	2,000	Ar/CO_2	(0.3)
D0 SAMUS	$\phi 3$	< 3	6,000		Ar/CO_2	(0.3)
ZEUS	0.9×0.9	< 10.2	100k	1,720	Ar/C_2H_6	(0.15)
VENUS	7×5	7.6			P10	1.3
MAC	$\phi 10$	4.5	3,600	1,500		
LAMPF	3.8×7.6	3.7	4,000	550		1
EMC[15]	$\phi 5$	2	1,100		Ar/C_2H_6	0.2

In many cases, only bench test resolution (in parenthesis) are available from publications. Resolutions of entire system in real experimental conditions are normally not published.

2 Open Cell Drift Chambers

Another type of muon chambers used in high energy experiments are multisampling drift chambers. In such kind of drift chambers, a number of sense wires are enclosed in a single gas volume (a super module). We call such type of chamber 'open cell' drift chamber. Sense wires are arranged in rows sampling muon track many times along its trajectory and measuring both its position and direction. In fig. 11 and fig. 12, the L3 muon chamber[16] and ZEUS forward muon chamber[17] are shown.

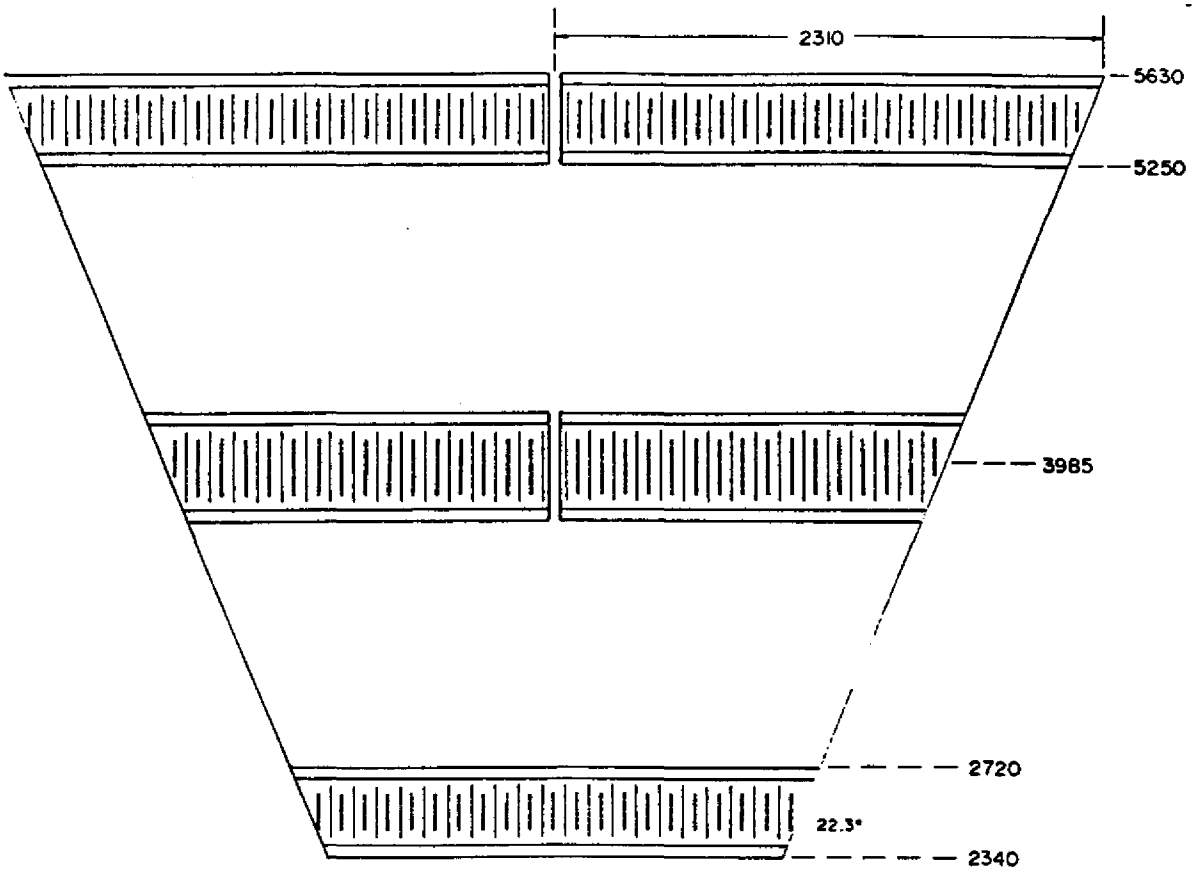
Many field wires are needed for each sense wire in this kind of design. A typical L3 muon chamber module contains about 320 sense wires and a total of 3,000 wires. (The effort of replacing the cathode wires by foil or screen has been so far unsuccessful.) The resulted electric field is extremely good except locations very close to wires.

Thick aluminium honeycomb plates are used to close the gas volume and for mechanical support.

Table 1. Parameters of Open Cell Muon Detectors

Detect	Cell Size cm	Length m	Ch.	Area m^2	Gas	Resolution mm
L3	20×1	5.6	27,684	1,000	Ar/C_2H_6	(0.15)
ZEUS Forward L*	10×1	8?	$> 250k$			

In order to reduce the channel counts of the detectors, both L3 and L* use the technique of sharing an amplifier by several sense wires in different octants.



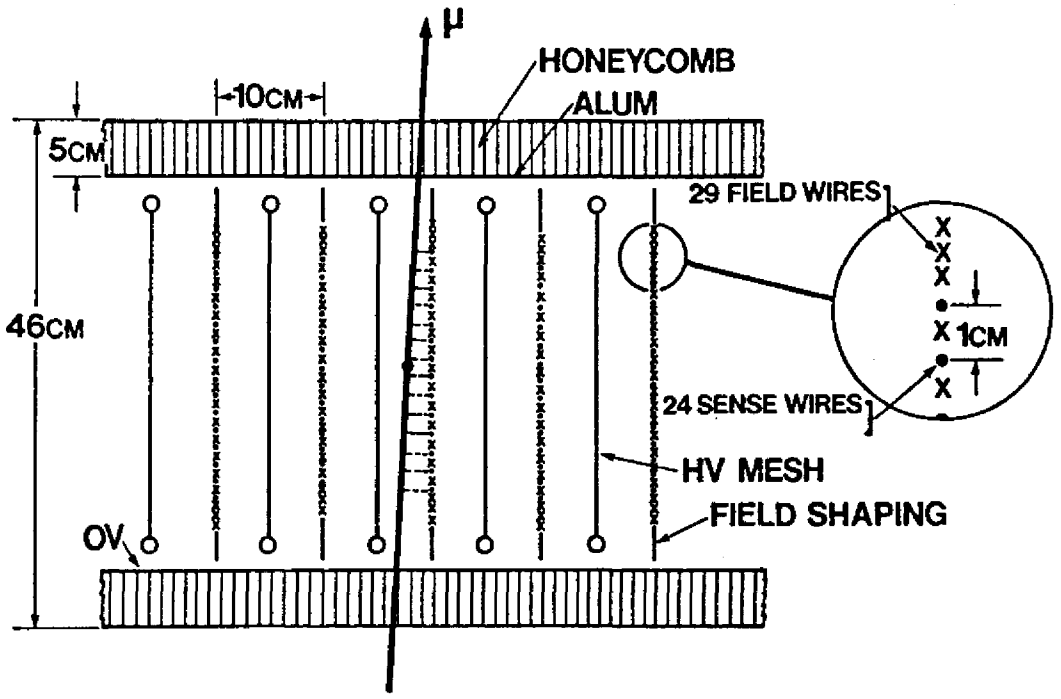
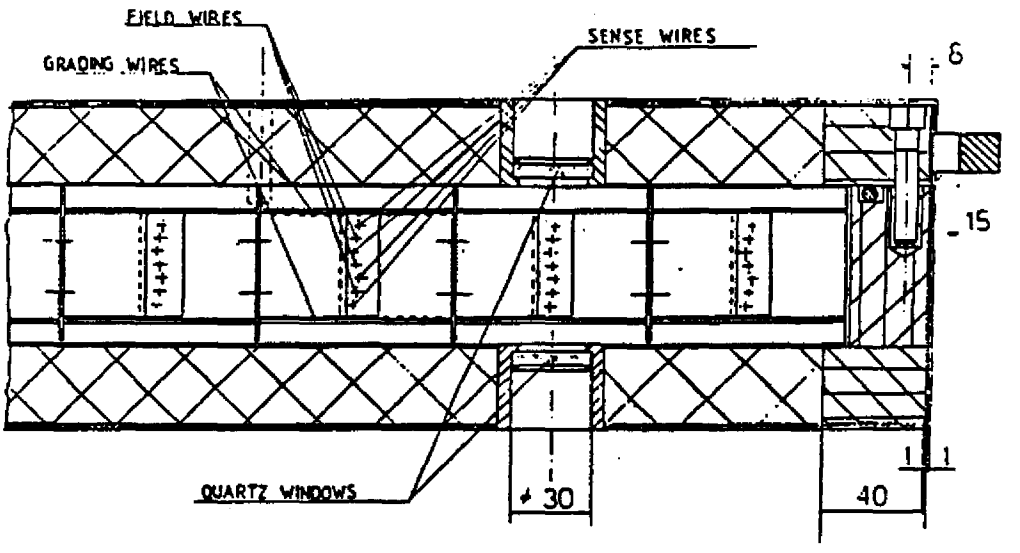
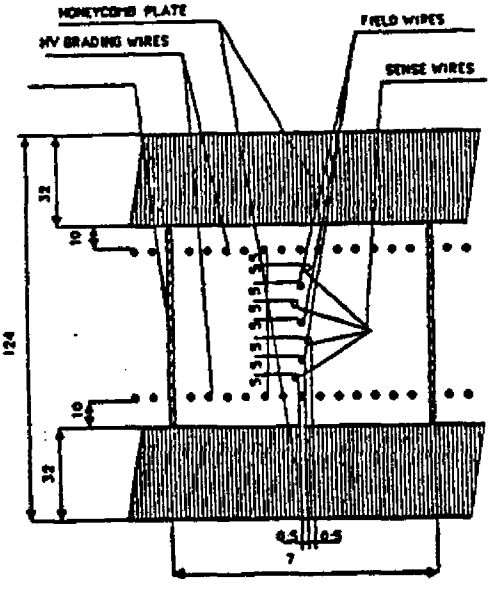


Fig. 11. Cross-section of a L3 muon chamber module.



Drift chamber mechanical structure side view.



Layout of a drift chamber cell configuration.

Fig. 12. Cross-section of a ZEUS forward muon chamber.

3 Muon Chamber Design Issues

3.1 Chamber Gas

The total gas volume of the SDC muon system will be huge, over 2 km^3 if D0 type of drift tubes are assumed. If filled with 50/50 argon/ethane, more than one ton of ethane gas are needed. Since all known saturated gas mixtures contain large portions of hydrocarbon, the safety requirements will likely prohibit their use.

Drift velocity curves of a variety of different gas mixtures are shown in fig. 13[18]. The drift velocity saturation property of non-explosive gas mixture argon/CO_2 are not bad if we choose the drift field strength properly. By comparing the two curves of argon/CO_2 90/10 and 80/20, we can speculate that 85/15 argon/CO_2 will be the mixture we want to use.

Unlike the saturated gas mixture, the drift velocity in a non-saturated gas mixture is more strongly affected by the electric field uniformity, the inaccuracy of the gas mixture and the environment factors. The chamber electrical stability is also worse without hydrocarbon quenchers. The gas gain has to be relatively low resulting small signal size. All these disadvantages of non-saturated mixtures make the chamber design more difficult.

3.2 δ Rays and Multihits

δ rays or ,in general, soft particles accompanying high energy muons can seriously affect the tracking chamber performance. Such particles can be produced by muons in the iron toroid or the drift tube walls.

δ ray production and its effects on drift tubes have been studies by the VENUS group for muons with energy below 10GeV.[2][19] Fig. 14 shows their Monte Carlo results. The saturated level of δ rays produced in the chamber wall entering the chamber gas volume increases as the wall thickness increases and saturates at 11% for iron and 14% for aluminium per incident muon. $20g/cm^2$ is required for this saturation. Signals from about one half of such delta rays on average will arrive the sense wire earlier than the true signal of the muon track, therefore, mess up completely the drift time measurements if a single hit TDC is used.

For extremely high energy muons, this situation will be a lot of worse. Such problem is expected to be serious in the forward region. Even in the central region, if we want to detect high energy muons from very heavy objects with good efficiency, we have to design the detector properly to handle this problem. We want chambers which are capable of resolving many closely spaced tracks at the trigger level.

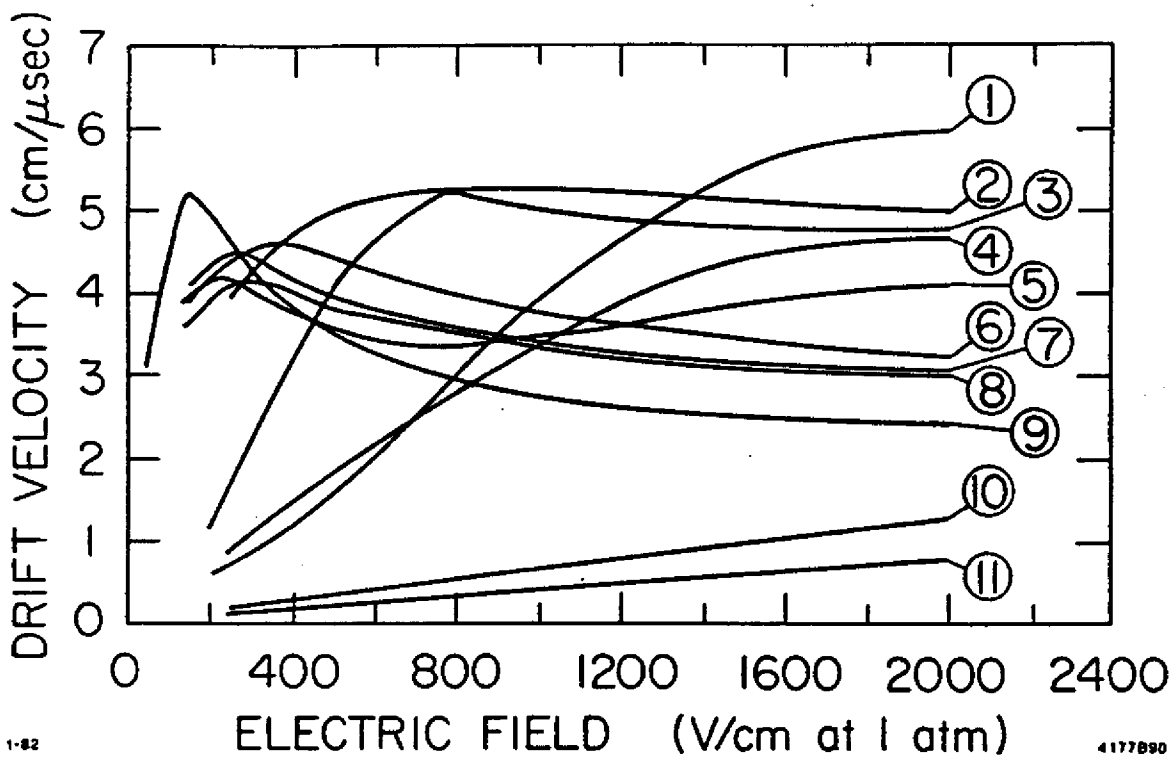


Fig. 13. Drift velocity versus the electric field for various gases. Gases are: (1) 80/20, Ar/CO_2; (2) 50/50, Ar/C_2H_6; (3) 90/10, Ar/CO_2; (4) $i\text{-}C_4H_{10}$; (5) 90/10, Ar/C_2H_4; (6) 90/10, $Ar/i\text{-}C_4H_{10}$; (7) 90/10, Ar/C_2H_6; (8) 90/10, Ar/C_3H_8; (9) 90/10, Ar/CH_4; (10) CO_2; (11) Ar.

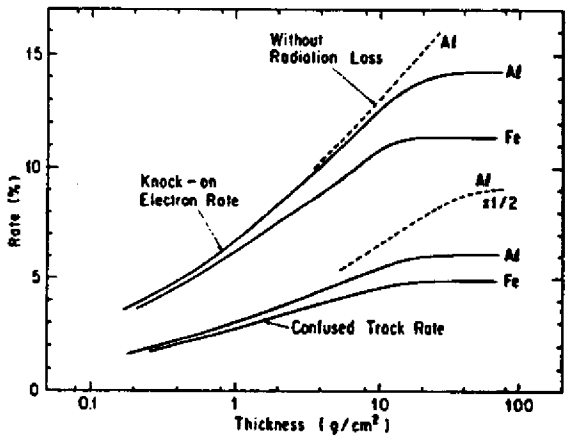


Fig. 14. Calculated knockon electron rate and confused track rate for aluminum and iron walls as a function of the wall thickness. The confused track rate is calculated in a drift-tube counter of 6.6×5 cm^2 in cell cross section. The dashed curves correspond to a hypothetical knockon electron rate in aluminum for which the energy loss by radiation is not included.

Some of the muon chamber systems designed in the past do have multihit capability. The UA-1 muon chamber readout is equipped with 125MHz pipeline TDC's. The L3 muon chamber readout uses LeCroy 500MHz pipeline TDC's.

It is not only the electronics but also the drift cell design determine the multitrack capability. Fro drift tubes with wide collection region, ionizations left by a charge track in the drift tube are all collected by the sense wire resulting a very wide pulse. Signals from adjacent tracks in a cell are merged together into one very wide pulse especially when these tracks not parallel with each other.

Unless the drift region is very narrow, resolving closely spaced tracks is impossible in a drift cell. (Solving this problem by electronics is extremely difficult.) Uniform and narrow drift field is clearly prefered.

3.3 Inclined Tracks

Only muon chambers placed at 90° will mostly receive muons penetrating chambers at normal incidence. The position resolution for large angle muon chambers will be degraded because they will receive mostly muons with large incident angles.

A dramatic example of this effect is shown in fig. 15. This is the measured relation between drift time and drift distance in the UA-1 chamber. The drift time and distance relation becomes very non-linear for inclined tracks. The position resolution worsened from 0.25mm to 1mm even after angular dependent corrections are made.

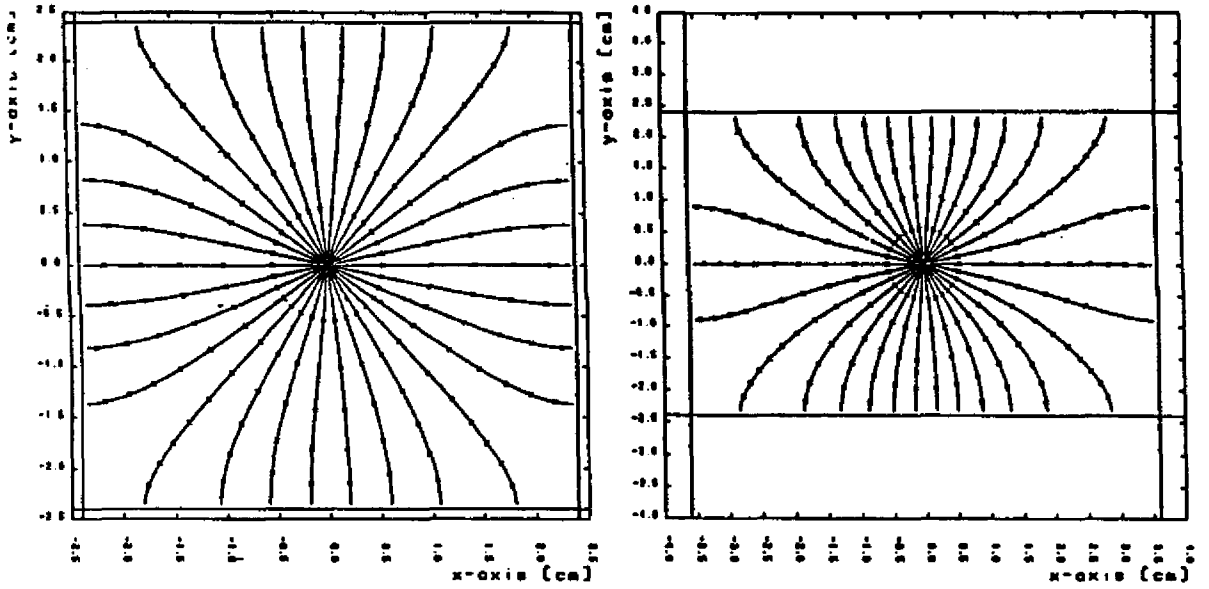
The measured D0 resolution function also has an angular dependent term as given before:

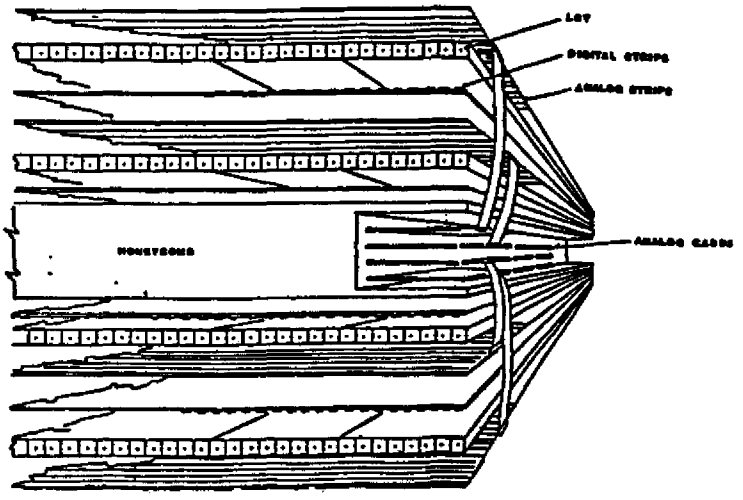
$$\sigma(\mu m) = 278 + 18\theta(degrees).$$

The authors of the report[20] stated that the origin of this effect is not understood at present.

This effect has been studied in some detail earlier by the JADE muon group[12] as shown in fig. 16. They concluded that a 5mm correction have to be made for 45° incident muons to compensate this effect.

From the point of view of measuring the angled tracks, simple drift tube arrangement does have obvious advantages as shown in fig. 17. Because of the symmetric field configuration, TDC information can be represented as circles. The angular dependence of the position resolution, therefore, does not occur. But, we do not want to use this type of drift tubes due to their many disadvantages.





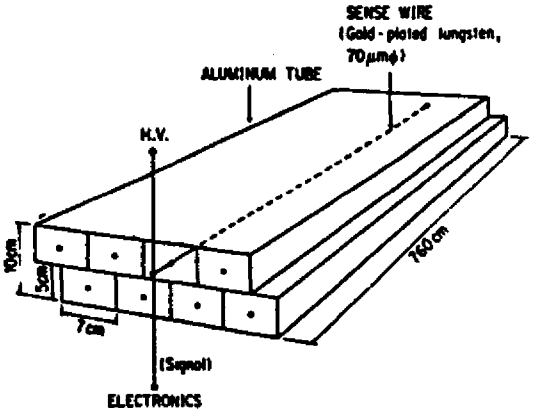


Fig. 1. Schematic drawing of a 8-cell module of the VENUS muon detector.

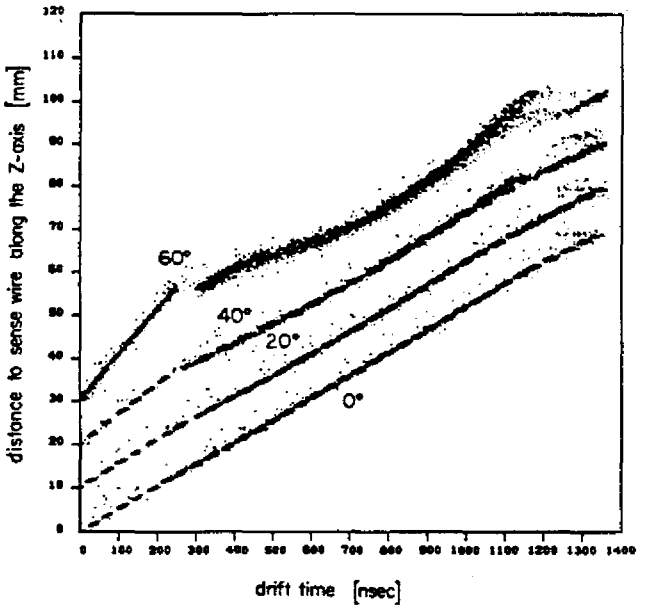


Fig. 15(a) Distance from the sense wire versus measured drift time for different track angles. The angle is defined in the plane perpendicular to the sense wire (90° corresponds to the z-direction).
Note, that the 20°, 40° and 60° data are displaced by 10mm each.

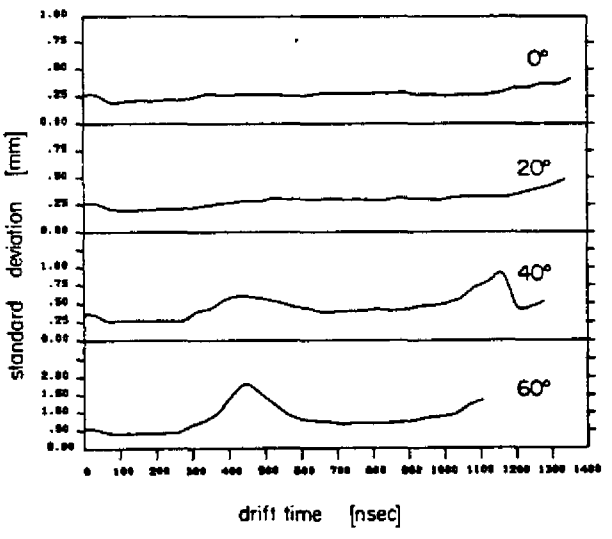


Fig. 15(b) Spatial resolution(rms) for different track angles as a function of drift time.

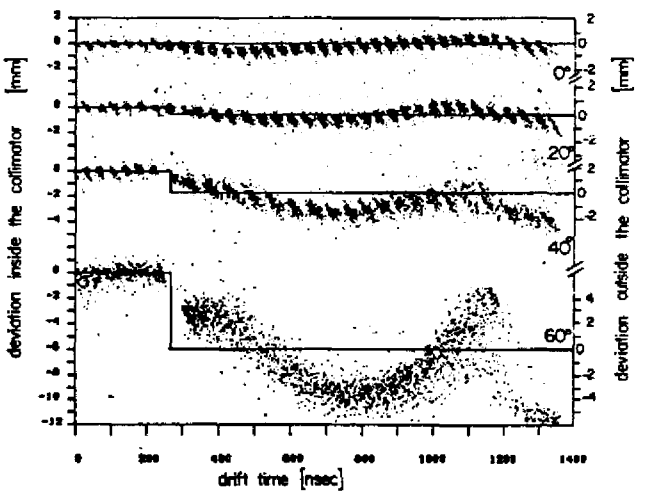


Fig. 15(c) Deviation from a space-time fit with constant drift velocity of 0.052mm/ns as a function of the drift time for different track angles.

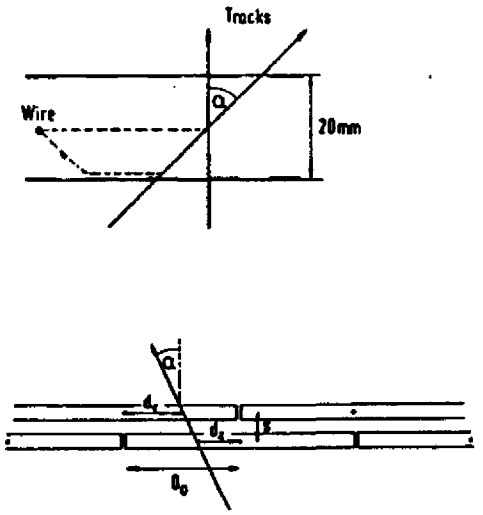


Fig. 16. (a) Shortest drift paths (dashed lines) to the signal wire for perpendicular and angled tracks. (b) Track incident at angle α to the fully overlapped chambers of layer 1.

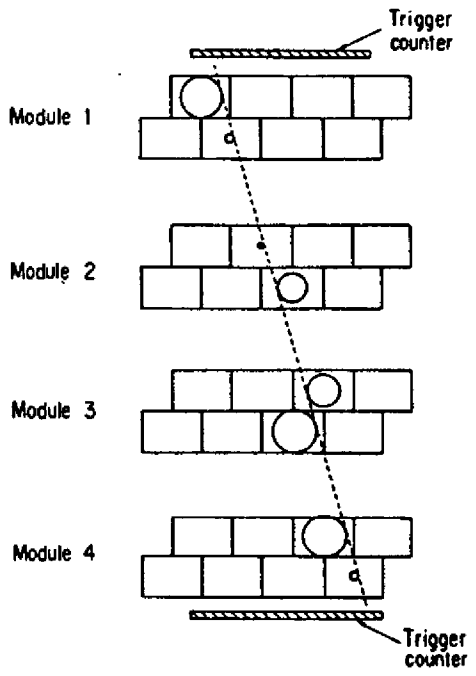


Fig. 17. Schematic drawing of the arrangement of four modules and two trigger counters in the cosmic ray tests. Also shown is a typical cosmic ray event. Circles represent TDC information and the dotted line the track obtained by the least-squares fit.

3.4 Streamer Mode Operation

Operating muon drift tube at streamer mode is very attractive since signals will have a very sharp rise time of a few nanoseconds and the signal size will be huge.

There are, however, potential problems. Stable operation in streamer mode using non-explosive gas which has fast drift velocity is not easy. The so called after pulsing can also be a serious problem. This after pulsing is caused by photoelectron emission from the aluminium tube wall. Since photons are copiously produced when chambers are operated at high gas gain, the probability of after pulsing can be much higher than 10% in many cases[11].

3.5 Diadvantages of the Open Cell Chambers

The open cell design as the L3 muon chamber has many attractive features as already discussed.

Their disadvantages are:

- Mechanical construction are extremely difficult for long chambers.
- High cost and potentially low reliability.
- Explosive gas may have to be used
- A broken wire makes a section of chamber dead.
- A soft electron (δ ray) will likely wipe out measurements of many wires.

It is unlikely that we can use this type of design for the SDC muon system except in the very forward region.

4 SDC Mon Drift Cell Optimization

Several cell designs for muon drift tubes were studied using a CERN drift chamber simulation package 'GARFIELD'. The motivation of this study is to find some simple cell designs which can meet requirements of SDC muon chambers. Our main goals are:

- simple and inexpensive suitable for large scale construction,
- capable of achieving $< 200\mu$ single wire resolution for all muon incident angles.
- capable of resolving multihits.

Configurations studied were rectangular cells with field shaping electrodes as shown in the following figures. Drift field uniformity and the width of the collection region for different aspect ratios, arrangements of electrodes and voltage settings are investigated and optimized.

Due to limitations of the drift chamber simulation package used here, electrodes are simulated by rows of wires. The electric field lines originated from the sense wire are plotted in the following graphs. The collection region, i.e., the central region in a drift cell in which the ionization produced by a muon track are collected by the sense wire, are clearly shown.

Electric field strength verses drift distance in drift cells is also plotted. In these plots, the curves are x-component of electric field. The solid curve is the field along the center line. The dashed curve is the x-component of the E-field along a line in x direction 3mm or 5mm from the center line.

$50\mu m$ diameter wire is assumed and the chamber is operated in proportional mode using Ar/CO_2 gas mixture. Conclusions of this study remain the same if a different sense wire diameter is used . In order to optimize the drift chamber performance, the mixing ratio of Ar/CO_2 has to be chosen properly. In order to optimize the drift speed saturation property and chamber stability, we assume an 85/15 mixture. The electric field strength on the surface of the wire is chosen to be 150-170 kV/cm in this study.

4.1 Aspect Ratio

Fig. 18 shows three different aspect ratios for a standard design of 8cm wide cell (4cm drift). Three different cell heights determined by the the I-beam heights are considered: 6cm, 5cm and 4cm.

For this simplest three voltage arrangement, the most important parameter which determines the drift field quality is the aspect ratio. In order to obtain acceptable drift field, the height of the cell should be at least 5cm. The drift field is greatly improved if the cell height is increased to 6 cm. A 4cm high cell (aspect ratio 1:2) produces unacceptable drift field in this case.

The drift field strength variation in a 6cm × 8cm cell shown in fig. 18a is about 15% which is perhaps acceptable. In this example, the sense wire is actually been held at ground potential which may simplify the chamber operation. On the other hand, the cathode high voltage has to be set quite high, at -5.5kV. Effects of different voltage settings will be discussed later.

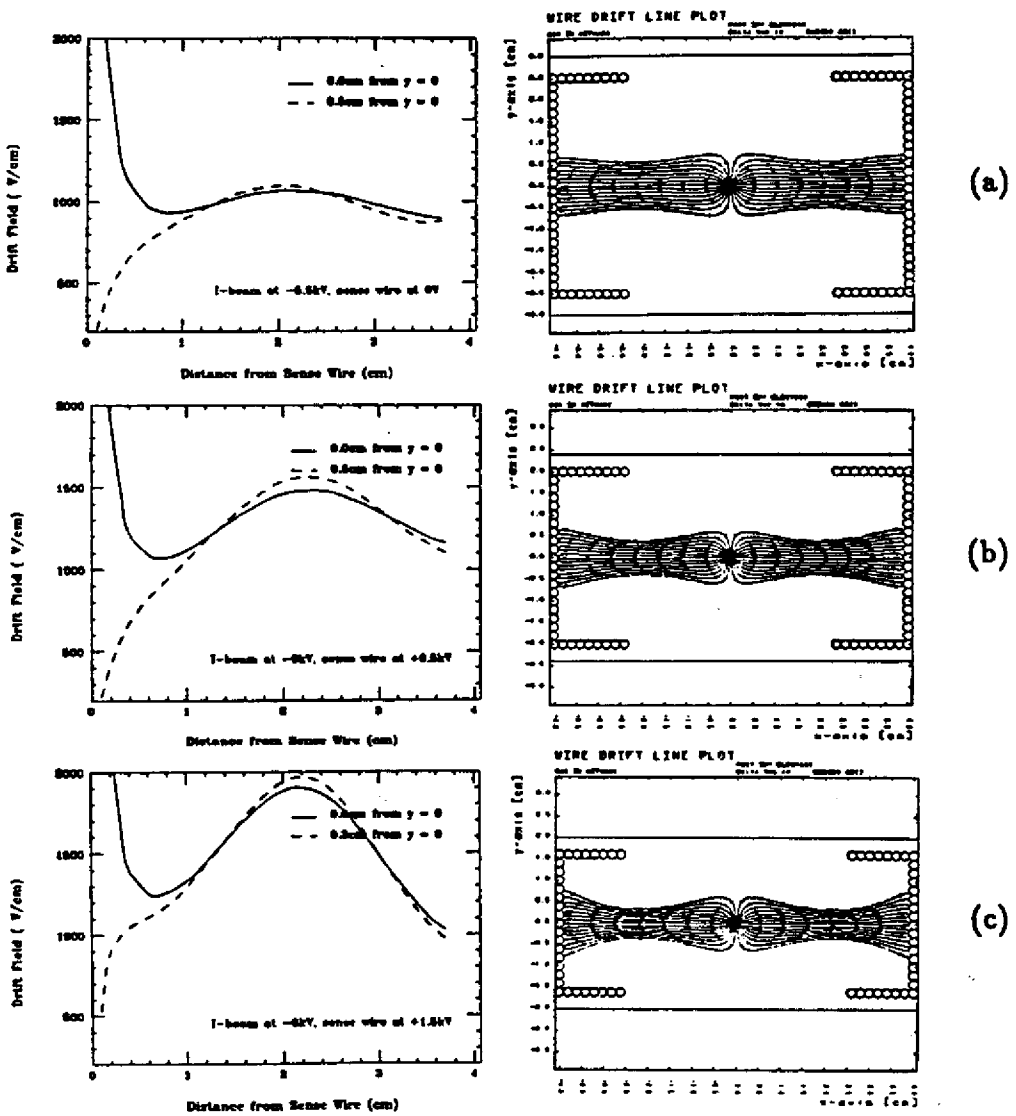


Fig. 18. Electrical field lines in three drift cells:
(a) 8cm × 6cm. (b) 8cm × 5cm (c) 8cm × 4cm.

4.2 Box vs I-beam

For the same aspect ratio, the drift field uniformity of a D0 type cell made of extruded tube with two inserted electrodes is better than the field uniformity of a standard I-beam type cell. This difference is clearly shown in fig. 19.

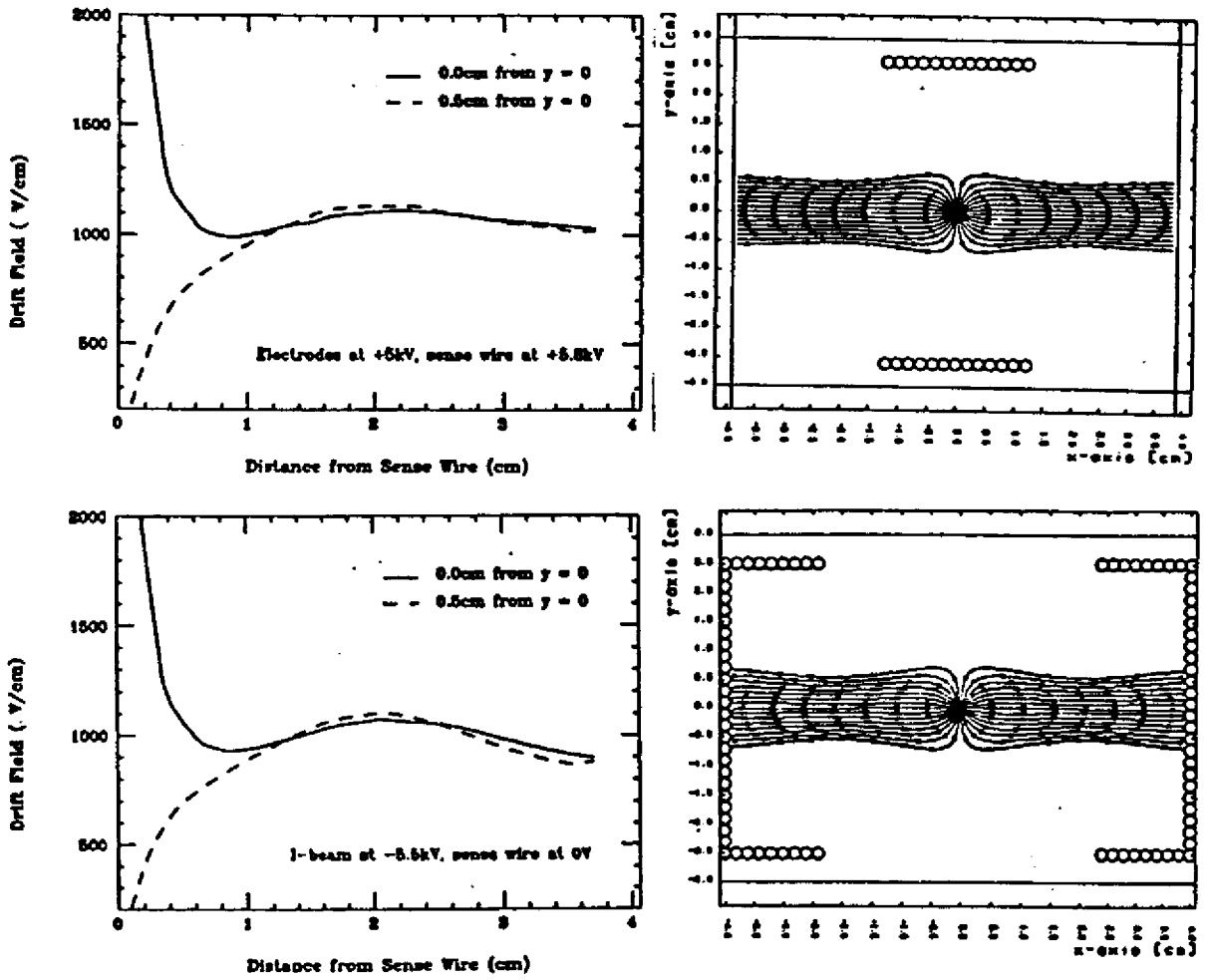
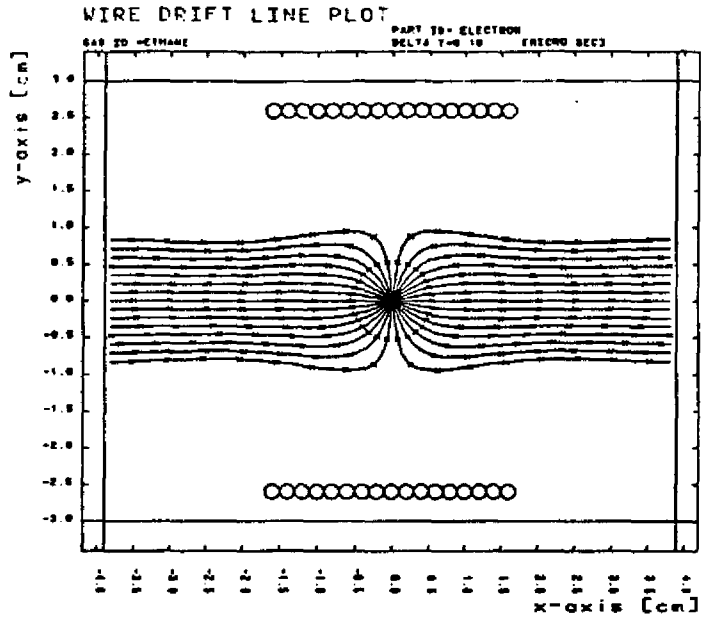
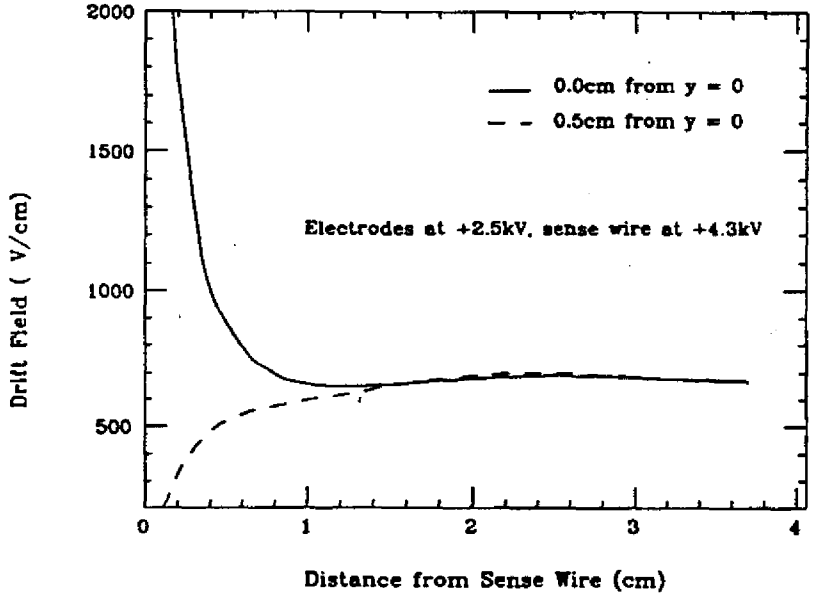


Fig. 19. Comparison between two types of cell structures.

Fig. 20 shows how does the drift field look like if we directly scale the D0 cell from $5.5cm \times 10cm$ to $6cm \times 8cm$. The field uniformity is quite good. The collection region, on the other hand, is wide.





4.3 High Voltage

Increasing the high voltage can reduce the width of the collection region. It is desirable to make this region narrow for the reasons of better two track resolution and for better measurements for inclined tracks, tracks crossing the drift field region at a large angle. However, the field uniformity becomes worse when we try to squeeze this region by increasing the high voltage. This effect is shown in fig. 21 for 8 cm wide cell. It is more dramatic in a 10 cm wide cell as shown in fig. 22.

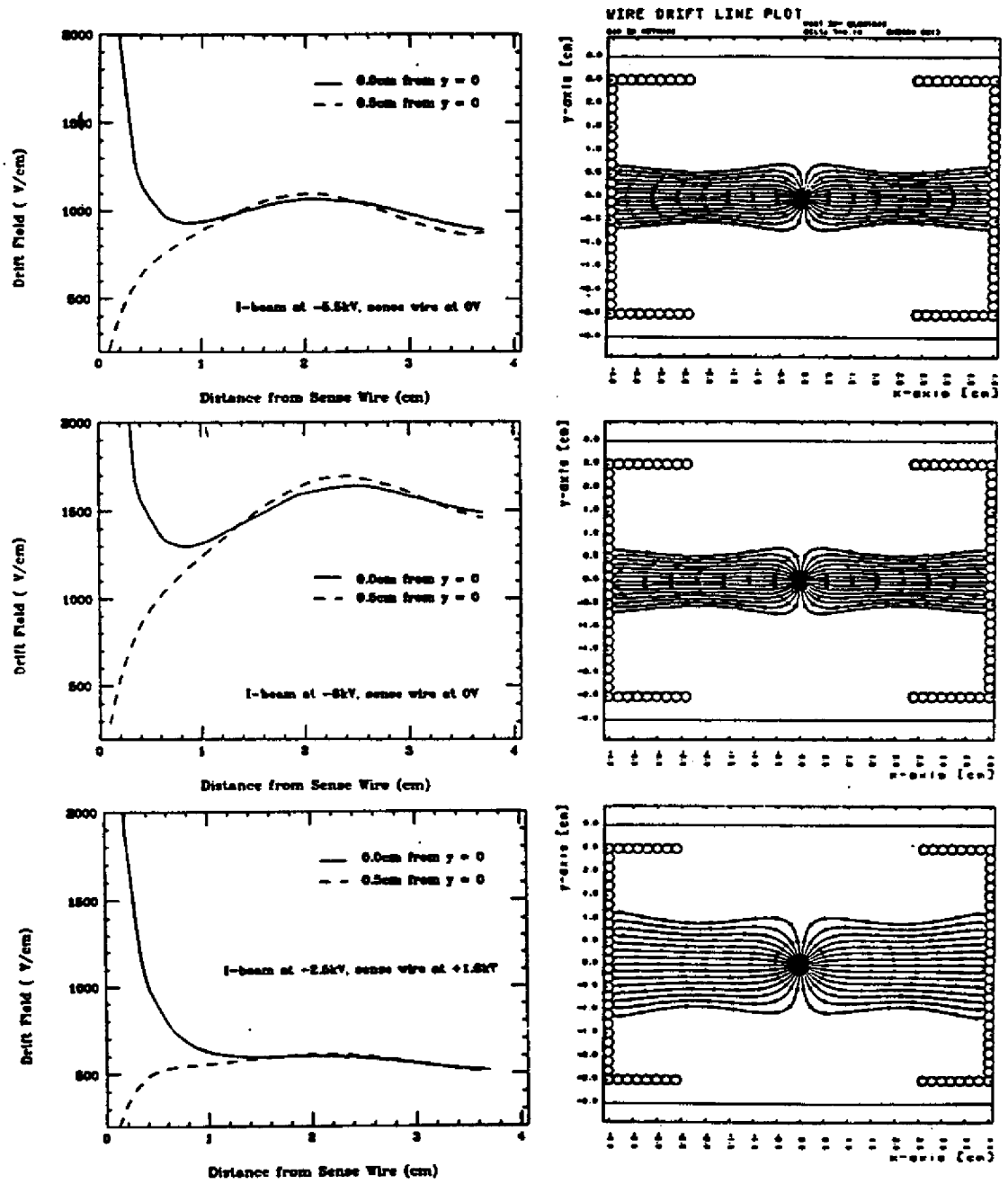


Fig. 21. Three different operating voltages for a 8cm × 6cm cell.

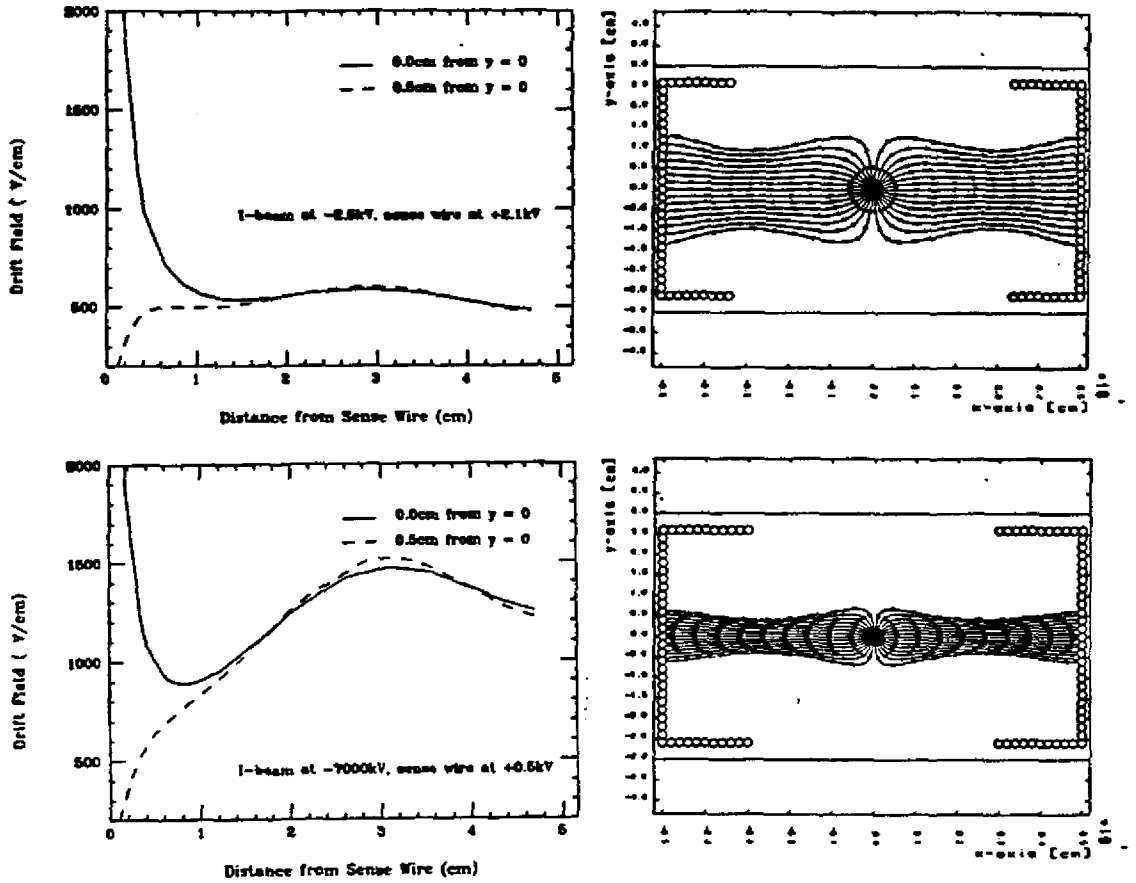


Fig. 22. Two different operating voltages for a 10cm × 6cm cell.

There are other reasons for narrow collection regions. In a 6cm high cell shown in fig. 18a, there is a gap of about 2cm wide between the top and bottom chamber walls and the boundary of the collect region. This gap improves the tube performance in two ways.

- The anode wire is not sensitive to keV photons and low energy electrons (up to about 50keV) produced by muons at the chamber wall. Such soft particles cannot penetrate this gap.
- After-pulsing due to absorption of photons by the aluminium wall will be essentially eliminated due to this gap. UV photons produced in avalanches striking the aluminium walls can produce secondary pulses. This phenomenon is particularly bad for Ar/Co_2 mixture because it is not very well quenched.

4.4 Field Focusing

Additional focusing electrodes can further squeeze the collection region as shown in fig. 23a and fig. 23b for box structure and the I-beam structure. The spacing between these two electrodes can be between 1cm and 2cm which controls the width of the drift field (ionization collection length). The serious problem of this design is that constructing long tubes with such design may be extremely difficult and wire supports will be necessary.

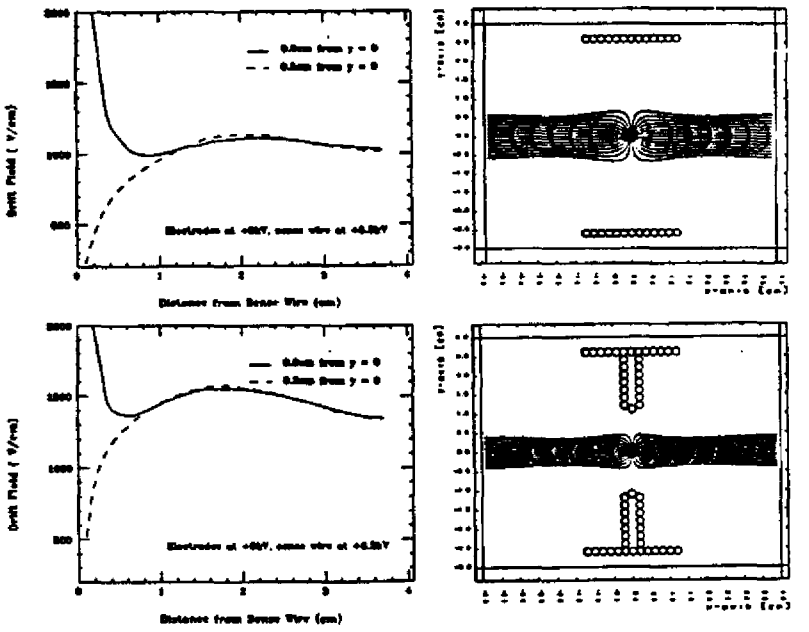


Fig. 23a. Effects of focusing electrodes in a box drift tube.

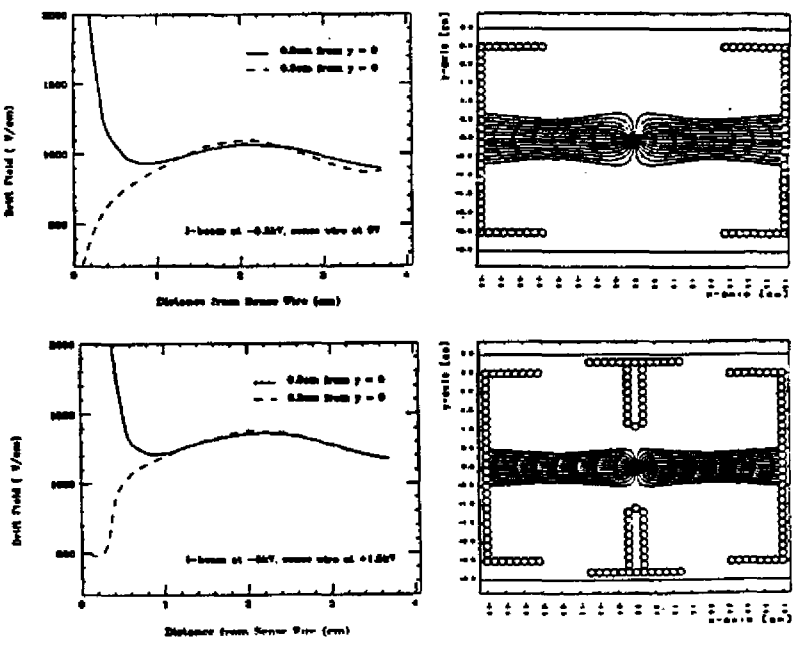


Fig. 23b. Effects of focusing electrodes in a I-beam drift tube.

4.5 A Four Voltage System

Another way of improving the drift field uniformity is, of course, adding more field shaping electrodes. For our geometry, introducing one more voltage level into the cell is already quite sufficient. Four additional field shaping electrodes have to be added. Drift field line plots of two types of cells, extruded tube and I-beam structure, are given in Fig. 24. Both cells have cross section of 8cm × 4cm. The field uniformity is significantly improved compared to the same size cell in fig. 18c.

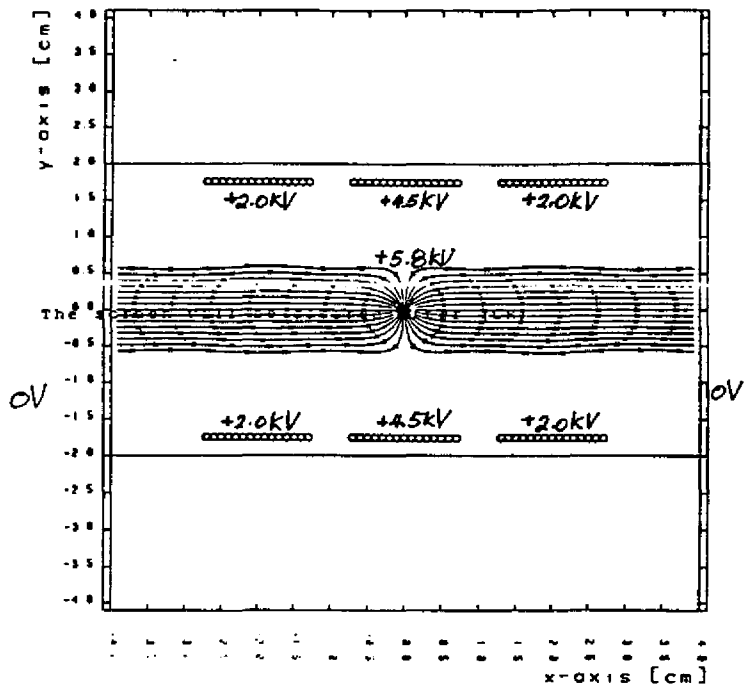
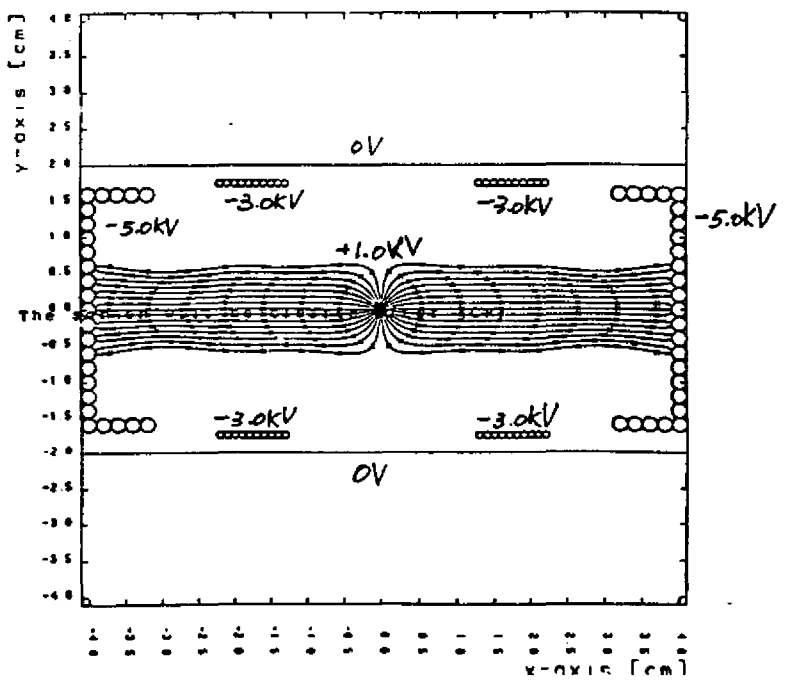


Fig. 24.



4.6 'Forward' Chamber Cell

The drift field is extremely uniform in a $4cm \times 4cm$ drift cell shown in Fig. 25 which may be a good candidate design for very forward regions where drift cells with small drift distance is desired.

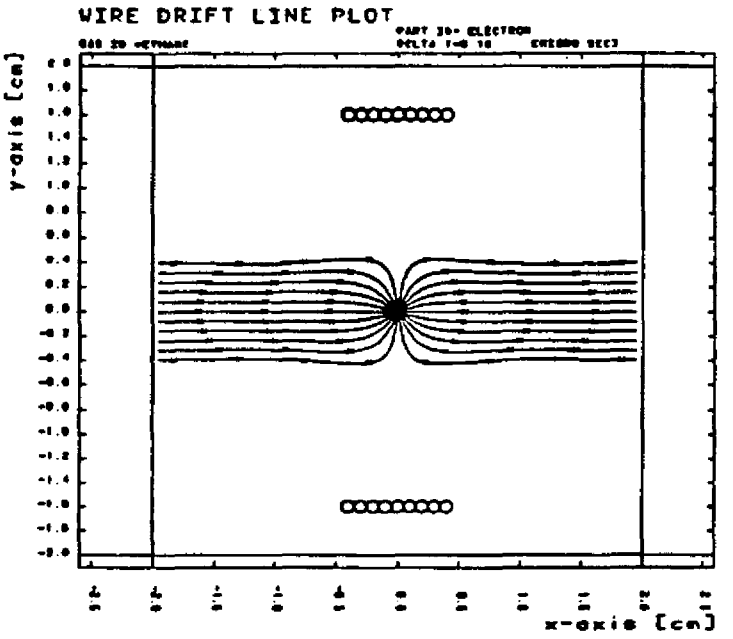
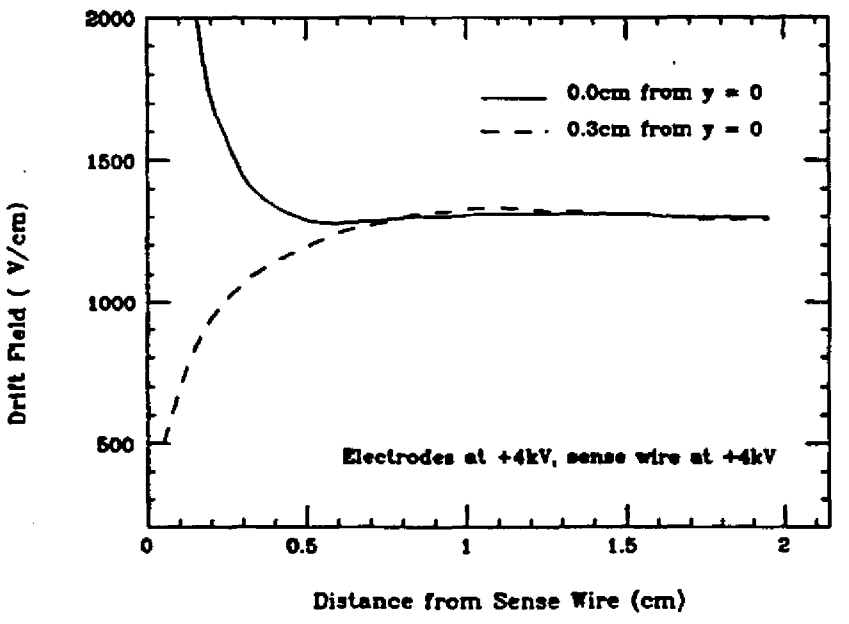


Fig. 25.



4.7 Cylindrical Cell

In solenoid based muon tracking systems such as CDF and L3 muon systems, high momentum muon tracks penetrate muon chamber planes perpendicularly. Angles between muon tracks and drift field lines in muon tracking chambers varies in a toroid based muon tracking system. The position resolution deteriorates as this angle decreases from $\theta = 90°$ towards the ends of the toroid barrel.

Such effect existed in many famous systems such as MARK-J, Jade, UA-1 and D0. The reported position resolution in these systems are far worse than our design goal of $250\mu m$.

This problem can be minimized by rotating the drift field in drift tubes at different θ for different sections of muon chambers. Such rotation can be esaily arranged if the cross section of the tube is a circle or a polygon. A example of such cell is shown in fig. 26.

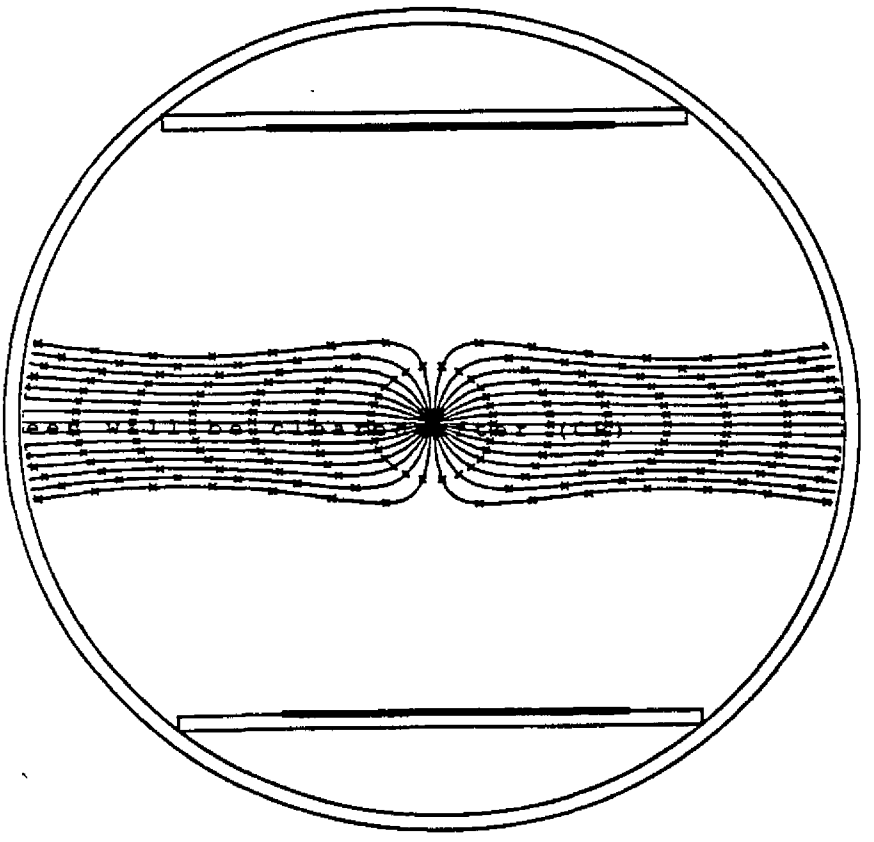


Fig. 26. Drift field lines in a cylindrical drift tube. The inner diameter of the tube is 7cm. Sense wire is held at +5kV. The two field shaping electrodes are at +4kV. Tube wall is at ground.

5 Conclusions

Very simple drift tubes with a minimum number of field shaping electrodes can satisfy all the design requirements for the SDC muon tracking chambers.

- Drift tubes as shown in fig. 26 with properly chosen field shaping electrodes and operational conditions is a good candidate for Θ-chambers. The diameter of such tubes can be 5cm-8cm and the orientation of the drift field can be adjusted such that a high momentum muon always nearly perpendicular to the drift field.
- The 8cm $\times$ 4cm drift cell with four voltage levels as shown in fig. 24 can also be considered, especially for Φ-chambers. The 4cm cell height helps to reduce the total thickness of the muon detector.
- The 4cm $\times$ 4cm cell shown in fig. 25 is suitable for the very forward region where the muon rate and chamber occupancy are high.

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