TPC R&D for an ILC Detector

Status Report from the LC-TPC groups [1] [2]

LC TPC groups

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Abstract

This report gives an overview of TPC studies as of October 2004. Representative results from various groups are shown and are preliminary. The R&D issues are discussed and are illustrated with examples, for the sake of conciseness, to characterize the status of the R&D.

[1]Proposal PRC R&D-01/03 of the DESY Physics Review Committee. The present status is of October 2004 and has been submitted for the DESY PRC Meeting of 28/29 October 2004.

[2]The WWSOC, the Organising Committee for the World-Wide Study on Physics and Detectors for the Linear Collider is forming an subcommittee for overviewing LC Detector R&D activities globally, in conjunction with America (USLCSG, NSERC-GSC), Asia (ACFA http://ccwww.kek.jp/acfa/) and Europe (DESY PRC).

[3]Working with DESY/MPI-Munich on beam tests at KEK using the MPI prototype.

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1 Introduction

A detector at a the International Linear Collider (ILC) will combine a tracking system of high precision with a calorimeter system of very high granularity. This detector, an example of which is proposed in the TESLA technical design report[1], will measure charged tracks with excellent accuracy, typically surpassing the precision of previously built detectors at LEP, the Tevatron, HERA or the LHC by a factor of 10. At the same time this detector must be optimized for the reconstruction of multi-jet final states stressing the jet energy resolution and the reconstruction of individual particles in jets. For the latter efficiency and reliability in reconstructing charged tracks is even more important than precision.

A typical design[2] of a "large" detector is the TESLA detector or the US Large Detector, which have a tracking system consisting of a large TPC as central tracker combined with silicon detectors for vertexing and intermediate tracking. The Asian large detector has gaseous tracking with TPC technology and is considering jet-cell-drift technology as an option.

In a previous document [3] the LC-TPC groups proposed to investigate the feasibility of designing and testing the TPC technology for this collider. To this end an R&D program was approved by the DESY PRC in 2001 and reviewed again in 2003. In this paper we report the present status of the R&D work and elaborate the next steps towards a full demonstration of the technology.

2 A TPC for the ILC

The requirements for a TPC at the ILC are summarized in the following table.

Momentum resolution	$\delta(1/p_t) \sim 10^{-4}$/GeV/c (TPC only; $\times$ 2/3 when IP included)
Solid angle coverage	Up to at least $\cos\theta \sim 0.98$
TPC material budget	$< 0.03\mathrm{X}_0$ to outer field cage in r
	$< 0.30\mathrm{X}_0$ for readout endcaps in z
$\sigma_{\mathrm{singlepoint}}$ in $r\phi$	$\sim 100\mu$m
$\sigma_{\mathrm{singlepoint}}$ in rz	~ 0.5 mm
2-track resolution in $r\phi$	< 2 mm
2-track resolution in rz	< 5 mm
dE/dx resolution	< 5 %
Performance robustness	$> 95\%$ tracking efficiency (TPC only), $> 98\%$ overall tracking
Background robustness	Full precision/efficiency in backgrounds of 10% occupancy (simulations estimate $\sim 0.3\%$)

Table 1: Typical list of performance requirements for a TPC at a ILC detector. The values are taken from one large-detector-type proposal but are similar for the different large detectors being discussed.

The anticipated resolution means that the intrinsic resolution of the TPC both in the direction of the drift and perpendicular to the drift need to be improved significantly. The operational conditions at the linear collider – long bunch trains, high physics rate – require an open gate operation without the possibility of intra-train gating between bunch-crossings should the delivered luminosity be optimally utilized. (Inter-train gating between bunch trains is of course possible.)

TPCs have been used in a number of large collider experiments in the past and have performed excellently. These TPCs were read out by wire chambers. The thrust of this proposal is to develop a TPC based on novel micro-pattern gas detectors (MPGDs), which promise to have better point and two-track resolution than wire chambers and to be more robust in high backgrounds than wires.

Systems under study at the moment are Micromegas[4] meshes and GEM (Gas Electron Multiplier)[5] foils. Both operate in a gaseous atmosphere and are based on the avalanche amplification of the primary produced electrons. The gas amplification occurs in the large electric fields in MPGD microscopic structures with sizes of the order of 50 μm. MPGD lend themselves naturally to the intra-train ungated operation at the ILC, since, when operated properly, they display a significant suppression of the number of back-drifting ions.

The R&D program proposed three years ago is in the process of addressing the novel issues which include the following (see [3] for more details).

- Operate MPGDs in small test TPCs and compare with wire gas amplification to prove that they can be used reliably in such devices.
- Investigate the charge transfer properties in MPGD structures and understand the resulting ion backflow.
- Study the behaviour of GEM and Micromegas with and without magnetic fields.
- Study the achievable resolution of a MPGD-TPC for different gas mixtures and carry out ageing tests.
- Study ways to reduce the area occupied per channel of the readout electronics by a factor of at least 10 with a minimum of material budget.
- Investigate the possibility of using Si-readout techniques or other new ideas for handling the large number of channels.
- Investigate ways of building a thin field cage which will meet the requirements at the ILC.
- Study alternatives for minimizing the endplate mechanical thickness.
- Devise strategies for robust performance.
- Pursue software and simulation developments needed for understanding prototype performance.

To meet these goals a number of institutes listed on this report joined together as LC-TPC groups, with the goal of sharing information and experience in the process of developing a TPC for the linear collider, and of providing common infrastructure and tools to facilitate these studies.

Meanwhile strong cooperations has developed between various subsets of groups depending on their common interests of study. The results of this work is also being shared with other groups doing related studies.

3 Facilities

A number of test facilities have been made available over the last couple of years which are used for TPC studies.

Figure 1: The 5T magnet in DESY with a test chamber inserted into the magnet bore. A 2T magnet is available at Saclay, and 1.2T/1.5T thin-walled coils are in use at KEK.

3.1 Magnets

At DESY a high-field magnet test stand was commissioned in late 2002 which provides magnetic fields of up to 5.3 T in a volume of 28 cm diameter by 60 cm length. This magnet is equipped with a cosmic ray trigger, and recently a UV laser has been added to allow high rate and multi-track measurements. In figure 1 a test chamber is seen as it is inserted into the DESY 5 T magnet.

A 2 T, 53 cm-bore magnet with homogeneous field is available at Saclay and is being used for studies of Micromegas TPCs with cosmics at the moment.

Recently groups from KEK/Asia became active in the research and are using two coils with 85 cm-bore at the KEK synchrotron, one with 1.2 T and the other with 1.5 T. These magnets are "thin-walled" (20% X_0) so that the test beams or cosmics penetrate the side of the coil into the TPC volume with little degradation.

3.2 Test Beams

DESY provides an electron test beam of up to 6 GeV electrons which has been used by several groups for TPC studies. The beam is equipped with a 1 T magnet and a Si telescope.

At KEK the groups have been using a 2-4 GeV/c hadron test beam with PID capabilities for TPC measurements with πs, kaons and protons.

One group has performed extensive tests of a prototype at a hadronic test beam at CERN.

Several groups have set up and are operating small scale cosmic ray test stands, which have been used to establish operational procedures for several prototype chambers and for first measurements of the properties of these chambers.

4 Gas Amplification Systems

A central part of the R&D activities for a LC-TPC is the investigation of different types of MPGD [7]. Devices studied are GEM foils and Micromegas. The GEM foils are for the most part produced at CERN [6] with a standardized hole pattern and thickness. Foils from other manufacturers were available as well, though only in rather limited quantities. Some studies were done with GEMs

[7] **M**icro **P**attern **G**as **D**etectors

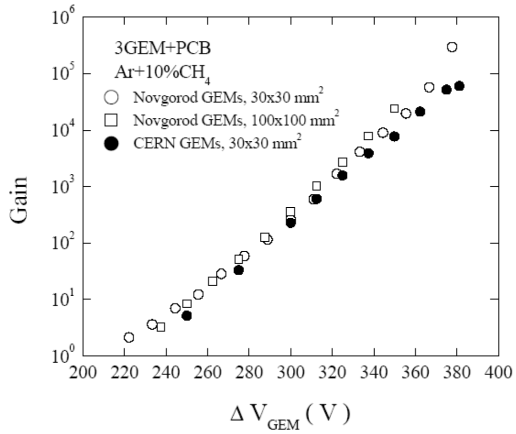


Figure 2: Gain as a function of applied voltage in triple GEM structures equipped with GEMs by different manufacturers.

produced by the Russia manufacturer Reper (Nijni Novgorod). Contact has been established with groups in Purdue University and Texas A&M, who have access to GEM foils produced by the 3M company in the US. In figure 2 an example of GEMs from different manufacturers is shown where no significant differences are found.

Micromegas are produced at the moment only by CERN[6] and are distributed to the different groups following this R&D line. In close interaction between mainly the groups from Orsay/Saclay and the CERN workshop, the layout of the Micromegas has been improved and their stability has been increased significantly. The large area copper micro-mesh, with a typical mesh size of around 50 μm are produced by the CERN workshop. The mesh is suspended on top of the readout printed circuit board by means of 50 μm high polyamide pillars with a diameter of 200 μm. These pillars have been formed on the readout board by etching a photosensitive film. The largest size Micromegas produced to date with this technique has a diameter of close to 50 cm.

To provide a comparison and explore the potential improvements end plates equipped with wires have been developed at the MPI in Munich. They have been built with significantly reduced spacing between wires to increase the achievable resolution.

5 Prototype TPC developments

A number of different prototype TPCs have been built by the different groups involved in the programme. The latest chambers were built to fit inside the high field test facility at DESY, the magnet at Saclay or that at KEK, to test out some first ideas about the mechanical and electrical structure of a possible future TPC. These chambers typically have diameters of 30 to 50 cm and drift lengths of up to 1 m. In figure 3 examples of two of the prototype TPCs are shown.

5.1 Field Cage Developments

The field cage of a TPC has to provide a uniform electric field for the drift volume, it has to contain the gas volume and it has to provide proper and sufficient high voltage isolation to operate the chamber. At the same time the material budget of the field cage should be as small as possible, to minimize the multiple scattering of particles on their way from the interaction point to the calorimeter.

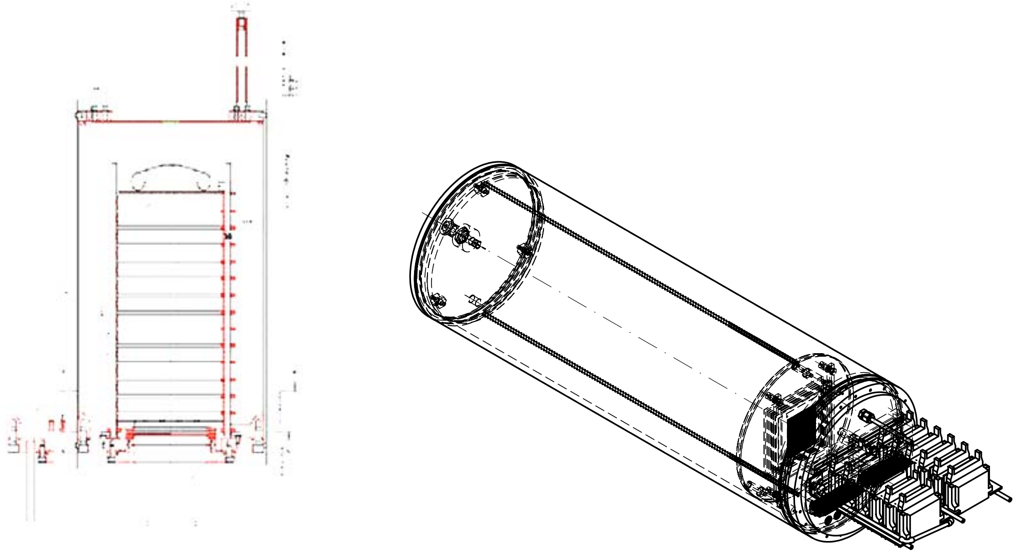


Figure 3: Examples of test TPCs as used in the R&D work. Left drawing: TPC as built by MPI Munich and used in the KEK test beam. Right drawing: TPC as built at DESY and being tested there.

The structure for the field cage investigated are composite structures. A high tensile shell made from either carbon fiber or glass fiber and epoxy composite is glued to a shell of very light honeycomb material. On the inside a layered structure of a highly insulating material like Kapton or Mylar provides HV insulation and the surface on which the electrodes for the field cage are mounted.

Two field cages were built along these principles. They differ in that one uses carbon-fibre and the other glass-fibre as structural material and in the way in which the resistive divider is mounted in the chamber. Currently experiments are under way to commission these field cages and to understand their properties. In future these techniques can be further developed and others tried.

An important function of the field cage is to maintain as homogeneous a field as possible. Simulations have been carried out to optimize the structure of field forming strips. It is known that the most homogeneous field can be achieved if the complete area of the field cage is covered with strips. Therefore the current design foresees strips on the inside and on the outside of the insulating layer, staggered by half a width of the strips. The effect on the field homogeneity is shown in figure 4. A uniformity of better than $\Delta E/E = 10^{-4}$ seems achievable. Currently work is underway to study the influence of possible field inhomogeneities on the overall resolution of the TPC.

5.2 Mechanical Developments

A central part of a MPGD TPC is the structure of the readout plane at the end. For the prototype TPCs build so far no attempt has been made to optimize the support structures for MPGD, nor has special attention been payed to a minimized material budget in the end plates. Work has started for the next generation of prototypes to develop a first realistic model of an endplate. In collaboration also with groups from the calorimeter R&D efforts within the linear collider community, studies are underway about the production and support of large area GEM foils. It is foreseen that the next generation of prototypes will try out some of the proposed methods.

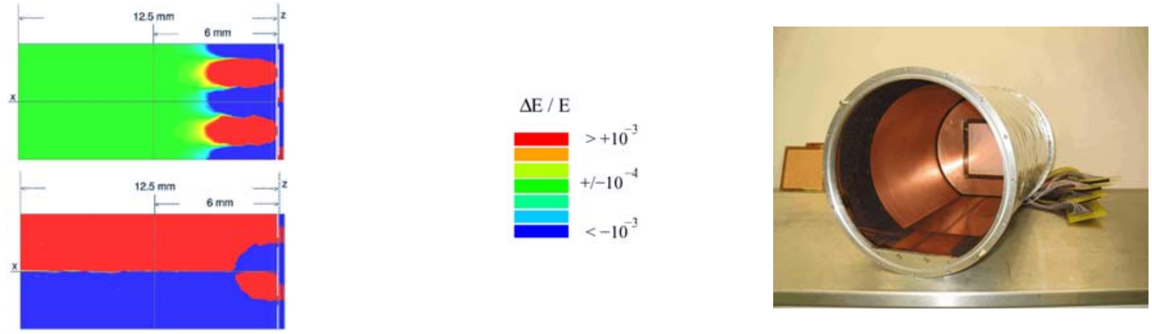


Figure 4: Left: The simulated electric field homogeneities for field cages with (top) and without (bottom) mirror strips on the outer side of the field cage. Middle: The plot on the right gives the scale of the relative deviations. Right: Photograph of the field cage.

5.3 Electronics Developments

An important part of the development of a new TPC is going to be the development of high density, low power and affordable electronics. The main requirements will be a rather small area per channel, to allow for small pads, little power dissipation and reasonably fast digitization.

At the moment most of the systems use existing readout electronics, which are not optimized for the fast signals expected from MPGDs. Electronics from the Aleph experiment has been adapted to be used in TPC prototype measurements and is available to LC-TPC groups for small number of channels. The DAQ system has been developed to operate in a modern VME environment and to be controlled by a LINUX workstation. The main limitations of this system are the long shaping time of the preamps, which are part of the system, the comparatively slow FADCs, which run at 11 MHz, and the small degree of miniaturization of the front end. More details on this readout electronics may be found in [7]. This system is being used by three LC TPC groups.

Three installations are available based on the Star electronics system. They have been adapted for use in a MPGD TPC in collaboration with the group from LBNL. While this system offers an improvement both in performance and in packing density compared to the Aleph electronics, it is still a system optimized for a TPC equipped with wire readout, and it is still approximately an order of magnitude too large for the final LC-TPC.

Recently work has started on a development of a first dedicated electronics version for LC-TPC work. It takes advantage of the fast MPGD signals and is highly integrated. In figure 5 a picture of a pre-amp card, and first signals from this card are shown. The Preshape 32 has been chosen as the front-end, providing 32 channels on one chip with a nominal peaking time of 45 ns [8]. It is planned to follow this with a 10bit ADC running at at least 40 MHz sampling speed.

An alternative development has been the investigation of a TDC based system for the readout of a TPC. It is based on a chip which provides a multi-hit TDC and a measurement of the pulse area by measuring the time above threshold for each pulse. The advantage of such a system is a decreased complexity, a possibility for a denser packaging and simpler operation. It is not clear though whether the inevitable loss of information by using a TDC only will compensate this or will eventually limit the performance of the TPC. First tests with a prototype system have been carried out and are currently being analyzed.

In future the readout-density requirement, which is mainly an ASICs problem, appears solvable because deep sub-micron technology is now avaiable (Star used 3.2-micron technology). The power

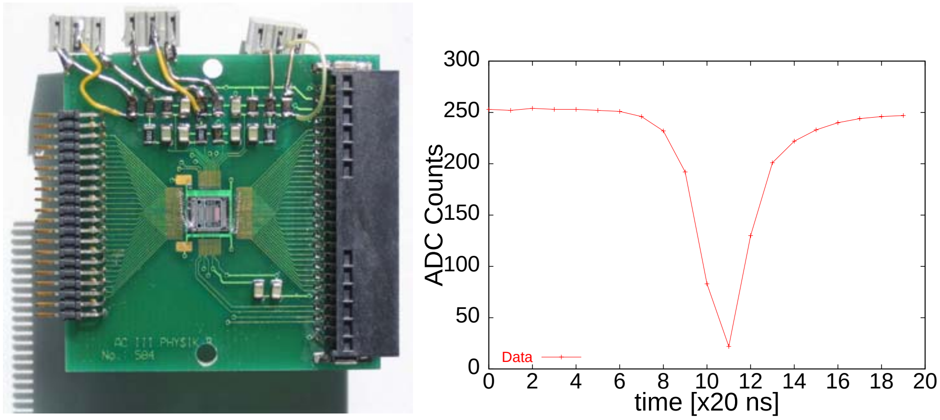


Figure 5: Photograph of the Preshape 32 chip bonded to a test board (left) and a first signal recorded with this setup

problem also appears solvable since one can take advantage of the time structure of bunch crossings at the ILC to ramp down the power between bunch trains. Dedicated work on a final electronics design for the LC TPC utilizing these aspects has not yet started, but a first iteration should begin soon.

5.4 Si Based Readout Concepts

The TPC as proposed for the linear collider has a large number of readout pads, each of which needs to be read out individually. A new concept has recently been proposed by which the readout planes are integrated into the read out chip. In this concept, the gas amplification is done by a "standard" MPGD, but the endplate essentially is a Si chip in which the readout electronics is integrated.

This concept offers the possibility to significantly reduce the size of the readout pads. Pad sizes small enough to be able to observe individual single electrons clusters formed in the gas can be envisioned. Rather than measuring charge integrated over a certain track length, as is always done in a traditional TPC, this device would basically count the number of clusters. The only limit to the resolution is the diffusion, which can be reduced by proper choices of gases and operating parameters. This concept will allow an excellent single hit resolution and an unprecedented double track resolution. It will be sensitive to the detailed structure of the charge deposition in the gas, including delta rays. Last but not least this concept promises to significantly reduce the amount of material present in the endplate.

Currently this Si chip is planned to be a CMOS based pixel matrix. The chip proposed for first test is the *"TimePix"* chip. Each pixel is equipped with a preamp, a discriminator, a threshold DAC and time stamping circuitry. It is intended in addition to fabricate a chip where the Micromegas grid is placed onto the readout chip by means of wafer post-processing technology. Such a sensor would replace the wires (or GEMs or Micromegas), anode pads, feedthrough, readout electronics and cables of TPCs. More details follow in the next section.

First test were carried out in a small test chamber with a "MediPix" chip, developed for medical applications. This chip provides a pixel matrix with amplification and threshold discrimination, but has no time stamping capability. Figure 6 shows the layout of the chamber and a photograph of the setup.

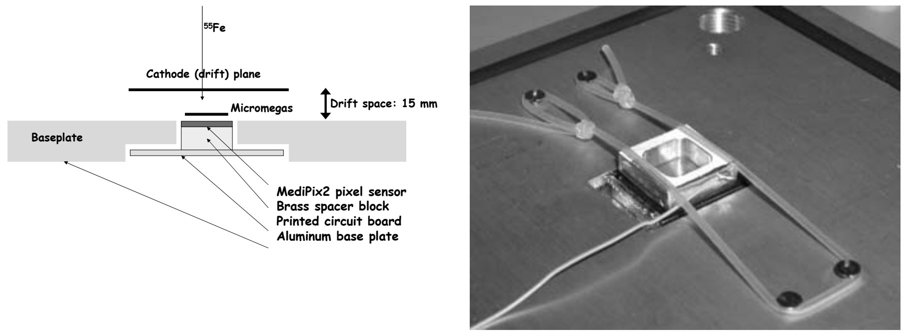


Figure 6: Left: The layout of the chamber with the MediPix2, the Micromegas and the drift gap. Right: The mounting of the Micromegas onto the MediPix2 sensor.

6 Prototype Results

In this section, preliminary results from measurements performed in a number of different test experiments are shown. These results cover the areas of exploring the basic operational parameters of a MPGD equipped TPC, and first measurements of the resolution achievable under different conditions. More details may be found in the publications by the individual groups, and in reports delivered at linear collider workshops, most recently the Durham workshop in September 2004[2].

6.1 Operational Experiences with MPGC TPCs

Within the context of the LC-TPC work six TPCs have been built and operated over extended periods of time. In general good stability and reproducibility of the operation has been found, independent of the type of the MPGD. As expected cleanliness plays an important role in preparing the chambers for operation, to avoid dust and other foreign substances from compromising the HV performance of the devices.

When designing a MPGD equipped system special care has to be taken to minimize the stored energy in the end plates. The GEM or Micromegas systems form essentially large capacitors relative to the readout plane. Under some circumstances enough energy can be stored in these capacitance to destroy the MPGD in the case of a sudden discharge. This can be avoided by subdividing the MPGD into smaller areas, and properly protecting them from the power supply to avoid sudden surges in the current.

At this moment it is too early to draw definite conclusions about long term stability and operability of such devices in a TPC. No indications have been found to the contrary so far in test TPCs, and the Compass experiment has operated large area GEMs and Micromegas in a hadron beam for several years without any damage observed. However the total accumulated operational hours and the total surface area equipped with MPGD is too small for final answers from our prototype TPCs. This will need to be studied with the next generation of prototypes, which should include larger readout areas.

6.2 Gas studies

The choice of the gas for a TPC is an important and central parameter. At the moment only a fairly small number of different gas mixtures have been investigated, a more systematic and complete study is still in the planning stage.

Gases investigated are variations of standard TPC gases such as Ar(93%)CH_4(5%)CO_2(2%)–"TDR" gas, Ar(95%)CH_4(5%)–"P5" gas, Ar(90%),CH_4(10%)–"P10", Ar (90%)CO_2(10%) and Ar (95%)Isobutane(5%). In the Micromegas tests an Ar(97%)CF_4(3%) mixture has also been studied.

When choosing a gas a number of requirements have to be taken into account. The resolution achievable is dominated by the transverse diffusion, which should be as small as possible. Simultaneously enough primary electrons should be created, and the drift velocity at a sensible drift field of around 200 V/cm should be around $5-10$ cm/μm. Hydrocarbons, which traditionally are used as quenchers in TPCs, have a high cross section for interaction with low energy background neutrons which will be crossing the TPC at a linear collider. Thus the concentration of these should be as low as possible, to minimize the number of background hits from neutrons. An interesting alternative to the traditional gases is a Ar-CF_4 mixture. These mixtures give drift velocities around $8-9$ cm/μm at drift field of 200 V/m, have no hydrocarbon content and have a reasonably low attachment coefficient at low electric fields. However at intermediate fields ($\sim$ 5 kV/cm), as present in the amplification region of a GEM or a Micromegas, the attachment increases drastically, thus limiting the use of this gas to systems where the intermediate field regions are limited to a few microns. This is the case for Micromegas for which this mixture has been shown to be suitable (figure 13). It has not been tested thoroughly for a GEM-based chamber.

6.3 Ion Backdrift

An important property of MPGDs is that they suppress naturally the backdrift[8] of ions produced in the amplification stage into the drift volume. This observation applies to both GEM foils and to Micromegas. In order to minimize the impact of ion drifting back into the volume, a suppression of roughly 1/gain is desirable. In this way the total charge introduced into the drift volume is about the same size as the charge produced in the primary ionization. This can be further reduced by gating between bunch trains.

The ion backdrift in a TPC is measured through carefully recording the currents on all electrodes. A total charge and current balance then can be established, from which the ion backdrift can be calculated. These studies were done for both GEM and Micromegas equipped TPC systems.

6.3.1 Charge Transfer Studies in GEM Structures

Using a small dedicated test TPC a systematic study of the current flows in a triple GEM structure was performed. The relevant quantities are the gain, the collection efficiency and the extraction efficiency of a GEM. The collection efficiency describes the probability that a charge arriving at the outer surface of the GEM is actually collected into one of its holes and sees gas-amplification. The extraction efficiency describes the probability that a charge created in the amplification process is extracted from the GEM in a way that it can be detected in a charge sensitive device behind the GEM.

Measurements have been performed for single and for multiple GEM structures, with and without magnetic fields. The resulting currents have been parameterized as a function of the applied electric fields across the GEM, and as a function of the fields in the structure.

Using the parametrisation of the charge transfer coefficients as a function of the electric fields, the ion backdrift is calculated as a product of charge transfer coefficients and single GEM gain factors. By scanning the whole parameter space and calculating the ion backdrift at every point, minima in ion

[8] We have called this "ion feedback" in the past, but that term is sometimes used to mean something different. We shall call it simply ion-"backdrift" or -"backflow" in this report.

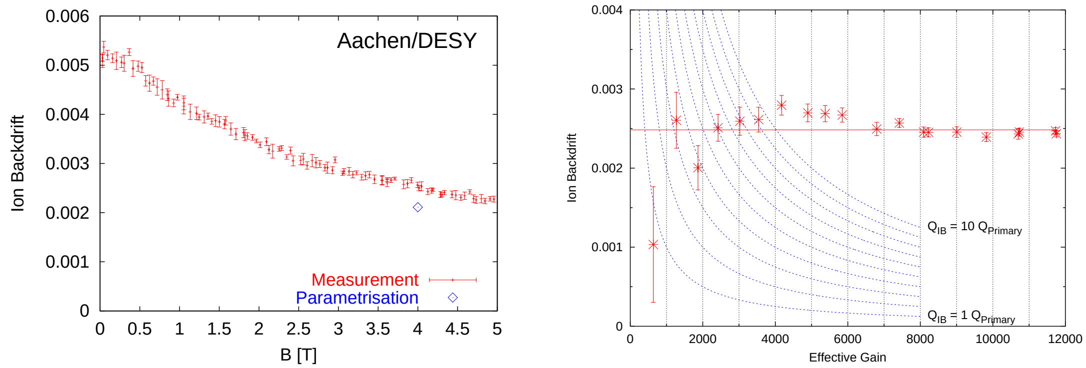


Figure 7: Left: Suppression of ion backdrift versus magnetic field. Right: Relative ion backdrift versus effective gain

backdrift can be found. Using this method, an ion backdrift of only 2.5 per-mille has been achieved in a magnetic field of 4 T.

Figure 7(left) shows the results from a measurement in the DESY 5 T magnet. It demonstrates that the ion backdrift decreases for increasing magnetic fields. This behavior is mostly due to an enhanced electron extraction efficiency as the field increases. One point in the plot also gives the prediction of the ion backdrift at 4 T from the parametrisation model discussed above. The offset from the measurement is due to the error propagation as the ion backdrift is a product of many charge transfer coefficients.

Figure 7(right) shows the dependence of the minimum reachable ion backdrift on the effective gain of the triple GEM structure. For each data point, all GEM voltages and fields were optimized and the resulting ion backdrift was measured. The relative ion backdrift is almost independent of the gain. Therefore, the choice of a low gain factor (if the signal to noise ratio is acceptable) would lead to a low absolute ion charge drifting back into the drift volume. At an effective gain of 1000, this charge would be only 2.5 times the charge from primary ionisation, thus approaching the requirements spelled out above.

The ion backflow has also been studied as a function of the gas mixture and the pressure applied to the chamber, and as a function of the gain of the GEM system. The results are summarized in figure 8. They show that the relative ion backflow is practically independent of the gas mixture and pressure.

6.3.2 Charge Transfer Studies in Micromegas Structures

Similar studies to those described in the previous section have also been performed for a Micromegas-based system [9].

In a Micromegas TPC, the drift and the multiplication region see very different electric fields, with a ratio of typically 300 between them. Charge which arrives from the drift region within one mesh gap is compressed to a funnel of a size of typically only a few microns. The light electrons then diffuse on their way towards the readout plane. Even though the typical diffusion for electrons in the high field region between the mesh and the readout plane is only around 15 μm (depending on field and gas, of course), this is still large compared to the size of the funnel. The ions are mostly produced towards the end of the electron drift, i.e., when they are maximally diffused. The ions drift back following mostly the field lines. Only those few which have been produced within the funnel

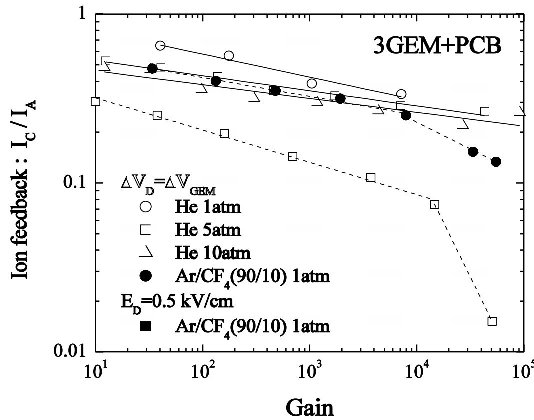


Figure 8: Ion backflow measured in a triple GEM structure, for different gas mixtures, different pressures, and as a function of the gain in the GEM system.

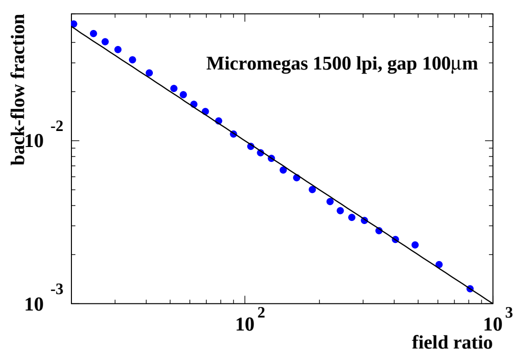


Figure 9: Ion backflow fraction as measured with Ar-10%CH_4. The line is the expectation from the inverse field ratio law.

will go back into the drift region, the rest will be absorbed by the mesh. It has been shown that the expected ion backflow can be described simply by the inverse ratio of the two fields.

This simple model has been tested successfully in a number of experiments. The results are shown in figure 9. Measurements and theory agree very well. From the plot it can be seen that a total ion backflow of a few times 10^{-3} seems possible.

6.4 Single Point Resolution Studies

One of the central requirements for a TPC at the LC is a good single point resolution. The goal is to reduce this to around 100 μm, which is well below point resolutions reached in previous large TPC.

The point resolution is studied in two different ways. First, very small chambers are used to explore the intrinisic limit of a gas and a readout geometry. Typically well collimated sources are used or X-ray beams to deposit well defined amounts of charge at a well defined point. Second, larger TPC prototypes are used with cosmic rays or with beams to explore the performance of a TPC under realistic conditions.

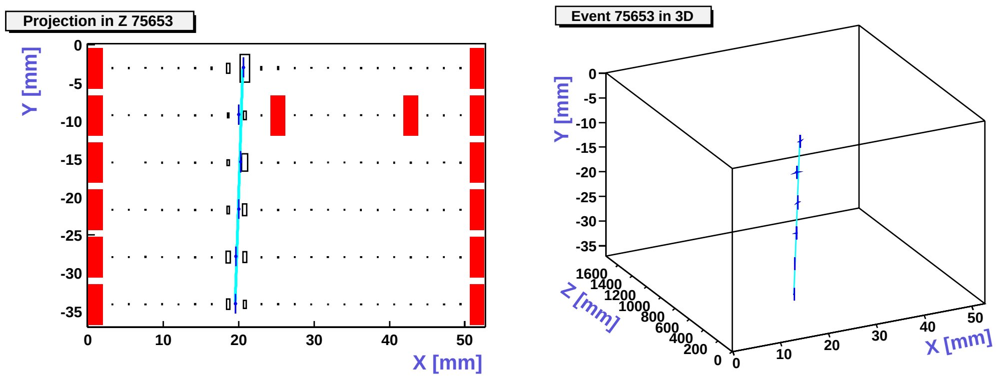


Figure 10: Event display of a single cosmic muon recorded in a 5T magnetic field with a GEM-equipped TPC; left: projection on the endplate; right: 3D view . The solid red boxes indicate dead readout pads.

6.4.1 Resolution in a GEM-based TPC

For the second method the point resolution is studied in larger prototype chambers using cosmic ray muons and particle beams. The measurements are performed as a function of a magnetic field. At DESY the chambers were mounted in the 5 T superconducting magnet such that the magnetic field was perpendicular to the GEM foils, as it will be in the LC-TPC. The gas volume consists of a composite frame enclosing a stack of two or three standard 10×10 cm^2 GEM foils.

The chambers were operated with a gas mixture consisting of the "TDR" gas and "P5" gas (see section 6.2). Some studies have also been done with Ar-CO_2 mixtures of different concentrations.

In figure 10 a simple event display of a cosmic ray in one of the test chambers is shown. Several thousand such events have been acquired in different magnetic fields and have been analyzed for the single point resolution. Data are available for the two gases mentioned above. The data are recorded with two different flash-ADC systems, which run at 12 MHz (Aleph) and 20 MHz (Star) respectively. For each pad the time of the hit is calculated based on the pulse shape. The exact algorithms used to derive the single point resolution are often different for the different analyses, so that comparisons must be done with care at the moment (this caveat is in the course of being resolved among the groups).

The method that provides the best estimate is one in which a reference track fit is compared to a fit using only one row, the residuals are fit to a Gaussian, and the standard deviation is determined. Two such measurements are performed, one when the reference track excludes the selected row, and one where the reference track includes the row. The resolution is given by the geometric mean of the two standard deviations. This has been shown in Monte Carlo simulations and in laser track studies to correctly reproduce the single row resolution.

The results from a measurement of the resolution in 0 T, 0.75 T and 4 T are shown in figure 11-left. The gas used was the TDR gas. A similar plot but for a P5 gas mixture is shown in figure 11-right.

The two resolution plots illustrate that the improvement of the point resolution from the magnetic field is small for fields larger than around 1 T, as is expected from theory and from simulation. The final resolution obtainable at small drift distances, where diffusion is negligible, is in either case larger than what would have been expected from theory. The exact reasons are at this moment not understood. Possible explanations lie in the method used (see above), systematic effects in the

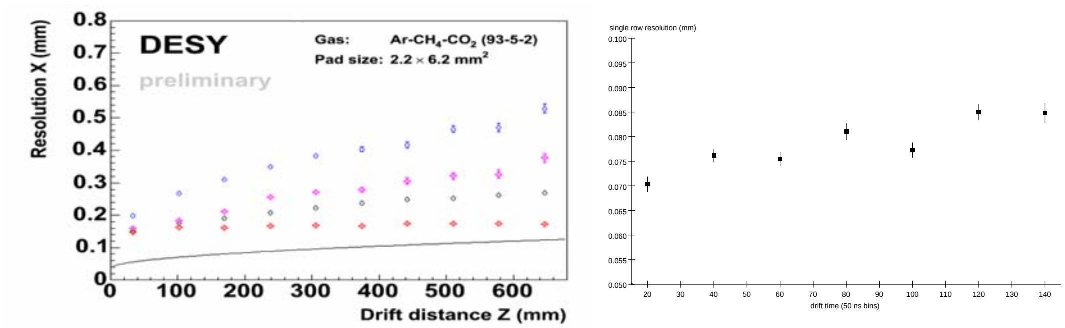


Figure 11: Point resolution measured in a GEM equipped TPC for different magnetic fields, and for different gas mixtures. Left: 93-5-2% Ar-CH_4-CO_2 (TDR gas), right: 95-10% Ar-CH_4(P10).

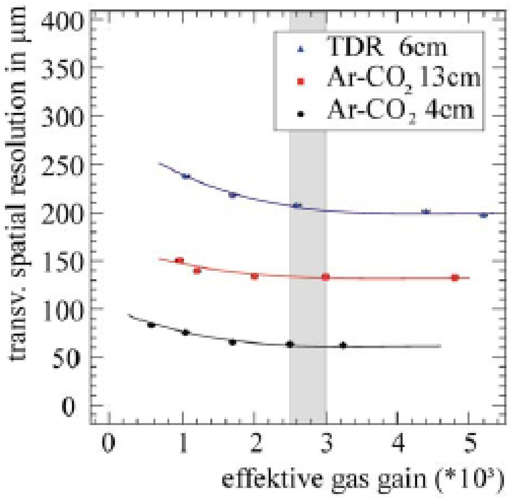


Figure 12: Point resolution as measured in a three-GEM TPC as a function of the gain.

chamber, misalignments, and possibly impurities in the gases used. In addition electronic noise in the existing setups has not been optimized and may also worsen the results.

To minimise the overall ion density in the TPC volume, the product of gain times ion backflow should be as small as possible. Thus to minimize the ion backflow a small gain is desirable. In figure 12 the point resolution for 0 T magnetic field is shown as a function of the gain in a three-GEM TPC.

From the measurement the goal of a point resolution of around 100 μm seems reachable, if the proper gas choice is made and if other effects are controlled tightly. However up to now, the diffusion limit of the resolution has not yet been reached, indicating the need for further studies and improvements of both the chambers, electronics and methods used. Nevertheless the measurements did establish the feasibility to operate a GEM TPC in high magnetic fields and obtain excellent point resolution.

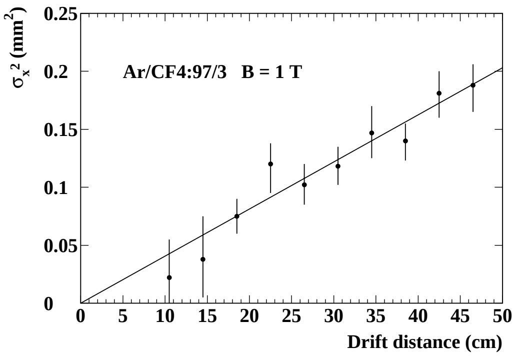


Figure 13: Track r.m.s. width measured in a Micromegas TPC at 1 T as a function of the drift distance.

6.4.2 Resolution in a Micromegas-based TPC

Using a test TPC of a diameter of 50 cm and a drift length of 50 cm, tests have been carried out in a 2.0 T magnet at Saclay with cosmic rays. The chamber has been operated with a 97-3% mixture of Ar-CF_4 gas. The recorded tracks are fitted with a circle fit in the $r\phi$ projection, perpendicular to the magnetic field lines. Six out of 10 possible pad rows are included in the track fit, the remaining four are used to estimate the resolution of the system. The square of the average of the r.m.s. hit widths (σ_x^2) are plotted against the distance and are shown in figure 13. The increase observed with increasing drift distance is typical for diffusion effects. The slope gives the transverse diffusion coefficient and is found to be $D_t = 64 \pm 8\mu\mathrm{m}/\sqrt{\mathrm{cm}}$ at B=1 T. This is roughly consistent with the theoretical expectation of $D_t = 85\mu\mathrm{m}$ expected for this gas mixture. The results of the measurement are illustrated in figure 13.

6.4.3 Resolution in a Wire-based TPC

To compare the results from the MPGD equipped TPC with those obtained with a classical wire based readout a TPC has been built and equipped with wires as well. The TPC is similar in size to the other ones investigated, but can be equipped with a wire readout plane, or a MPGD readout plane. Measurements were performed in a test beam at KEK where a 1.2 T magnet is available.

The wire readout consists of a plane of sense wires which have a diameter of 20 μm and are spaced with 2 mm pitch. To have very good two-track resolution, the sense-wire plane is placed 1 mm above the pad plane onto which the signal from the gas-amplification at the sense wires is induced. The pads are readout by the Aleph-electronics based readout system.

The point resolution obtained in this setup is shown in figure 14.

6.5 Methods to Improve the Resolution

As discussed in the previous sections, the resolution obtained in MPGD TPCs so far has been somewhat worse than expected from diffusion in the drift region. This is partly due to single-pad hits for short drift distances. Therefore various techniques for “spreading the charge” are under study.

In the case of GEMs, it has been shown that diffusion between the last GEM and the pad plane can defocus the charge cloud to about 0.4 mm width (depending on gas/operating parameters). Further it

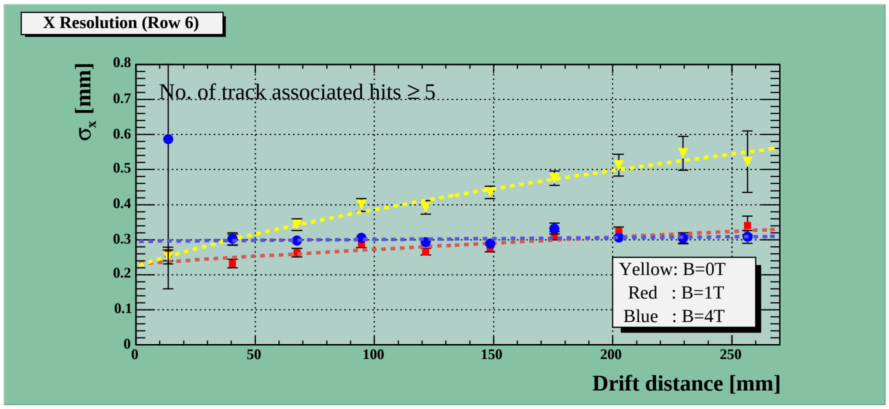


Figure 14: Point resolution measured as a function of the drift distance in a wire TPC with 1 mm sense-wire-to-pad-plane gap; 0 T and 1 T points are from test-beam data, 4 T points are from cosmics.

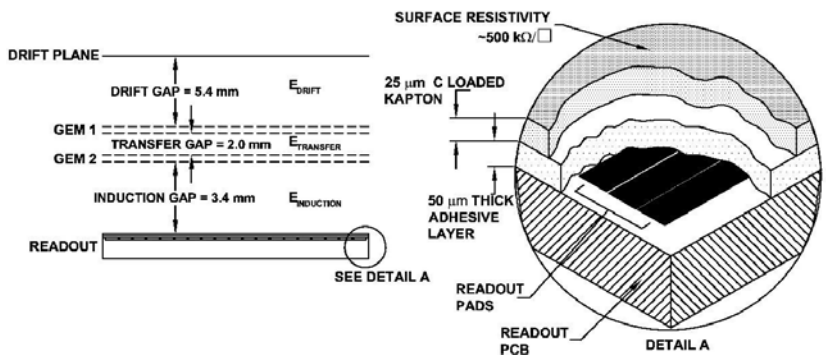


Figure 15: Schematics of the resistive anode double-GEM detector for charge dispersion studies.

has been shown that the pad width can be about 3 times that of the cloud and still allow enough charge sharing. Thus the 2 mm pad width used for several prototypes is nearly matched to these conditions, but further work is needed to determine the optimal pad size using this defocussing property.

A new concept has been developed for precise measurement of charge positions in an MPGD with wide pads. A high surface resistivity film, used for the anode, is bonded to the readout plane with an insulating layer of glue (figure 15). The resistive anode film forms a distributed 2-dimensional RC network with respect to the readout plane. A localized charge arriving at the anode will disperse with a time constant determined by the anode surface resistivity and the capacitance per unit area. With the initial charge covering a larger area with time, wider pads can be used for position determination. First proof-of-principle experiments with a resistive readout plane were performed using a collimate soft X-ray source [10]. To study this method in a real TPC a test TPC was modified to accept a resistive readout plane. The gas amplification was via a double GEM system. Figure 16 shows a TPC charge dispersion pulse for two pads. Both the pulse rise time and the decay time depend on the position of the charge with respect to the pad. The charge collecting pad shows a fast signal. The signal on the adjacent pads have a slower rise and decay time.

To extract the optimal resolution a detailed knowledge of the pad-response function (PRF) is

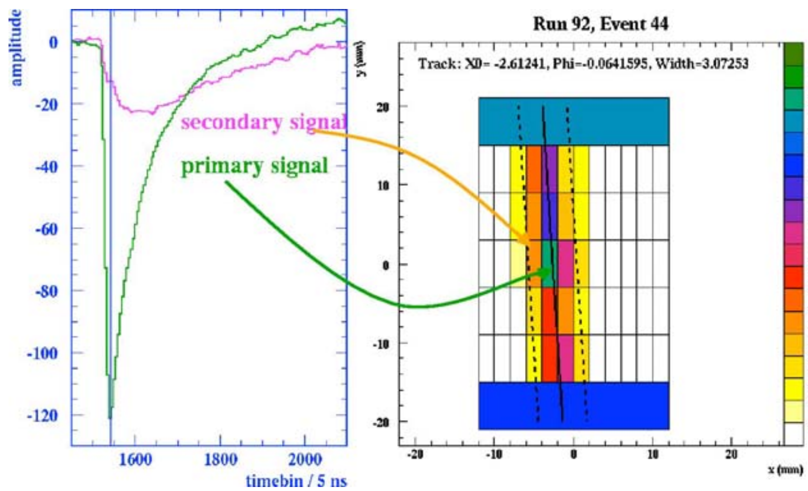


Figure 16: Charge dispersion signal on a charge collecting pad and its neighbor for a cosmic ray track in the TPC. Ar-CO_2/90%-10%.

needed. The pad response function is measured using cosmic muons.

The charge dispersion signals are affected by non-uniformities in the anode resistivity and the capacitance per unit area. Position measured from PRF need to be corrected for local RC distortions. The bias corrections were also determined from the internal consistency of the calibration data set.

Figure 17 shows the resolution measurements for Ar-CO_2 with and without charge dispersion. The resolution with charge dispersion is significantly better than without. Apart from a constant term, the dependence of resolution on drift distance is consistent with diffusion.

A detailed simulation has been done to understand the characteristics of charge dispersion signals. Initial ionization clustering, electron drift, diffusion effects, the MPGD gain, the intrinsic detector pulse-shape and electronics effects have been included.

In summary the charge dispersion on a resistive anode seems a feasible method to improve the single point resolution and bringing it close to the diffusion limit, without increasing the number of readout channels beyond reason. In the future the studies will be extended to also include Micromegas TPCs.

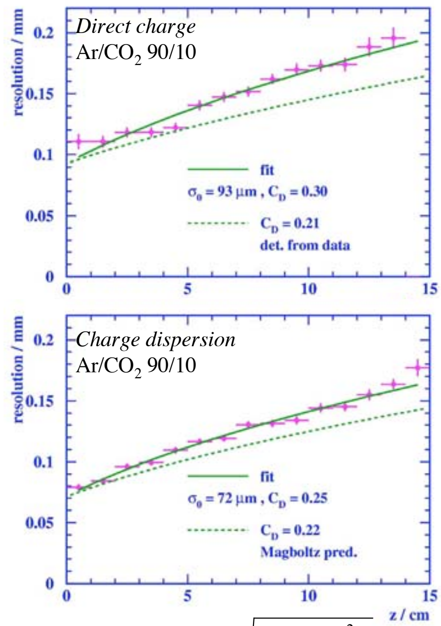
6.6 Double Track Resolution Studies

The resolution of close-by tracks is very important in the densely collimated jets expected at the linear collider. The specifications call for a possible resolution of a few mm, which is about an order of magnitude better than in previous TPCs.

Measurements of this quantity are just starting, and no final results exist yet. Techniques used are test beams on the one hand, UV-laser beams on the other.

In figure 18 an event recorded at the DESY 6 GeV test beam is shown, where a thin target has been inserted in the beam in front of the TPC. This created a spray of particles which are then recorded in the TPC.

An alternative approach is the use of a UV laser to produce close-by tracks under controlled conditions. First measurements with a laser based system were done in the 5 T magnet in the summer of 2004. A preliminary plot of the point resolution on close by tracks measured with this setup is shown in figure 19. The horizontal line indicates the single row resolution for single tracks,



$$\sqrt{\sigma_0^2 + \frac{C_D^2}{N_e} z}$$

Figure 17: Charge dispersion improves TPC resolution over that from direct charge detection for low diffusion gases like $ArCO_2$.

and it is seen that the resolution is unaffected for parallel tracks that are 4 mm apart. The resolution degrades somewhat at 2 mm separation, and is much worse at 1 mm separation. The preliminary results indicate that good track information can be reconstructed from tracks that are separated by about one pad width.

6.7 Drift Velocity Measurements

An important parameter relevant for the performance of the TPC is the drift velocity. This quantity is also quite sensitive to impurities in the gas, and can therefore be used to monitor the gas supply into the chamber.

The drift velocity measured and compared to the theoretical expectation is shown in figure 20. The solid curve superimposed to the measured points for the TDR gas is the prediction of the drift velocity as calculated using the Magboltz program which reads its gas data from the Garfield program. Excellent agreement between measurements and calculation is seen.

6.8 Track Distortion Studies

Charge produced in the drift volume of the TPC - from primary ionization as well as from back drifting ions - will distort the drift field, and introduce systematic errors in the final resolution achieved. In order to study the size of these effects a series of dedicated measurements has been performed. An ionizing ^{55}Fe-Source has been mounted on the cathode of the test TPC. This leads to a continuous flow of ions drifting from the readout to the cathode, forming an ion tube. At the same time events are

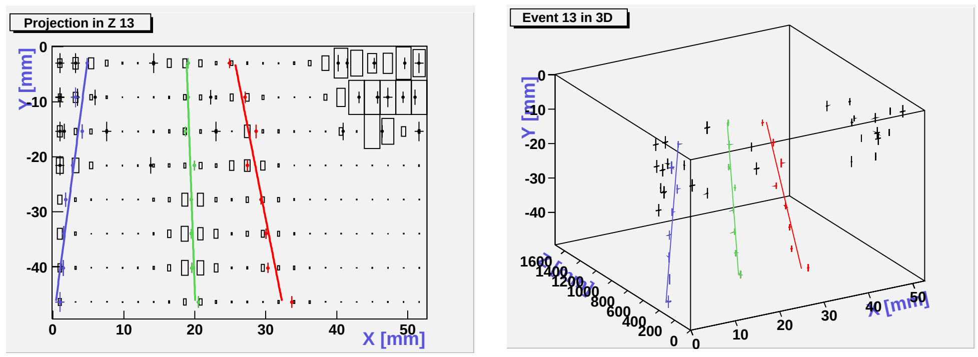


Figure 18: Display of a multi-track event recorded at the DESY test beam

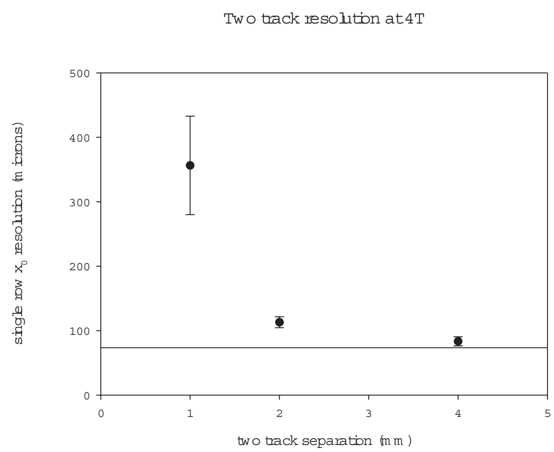


Figure 19: Single row resolution recorded in laser-induced two-track events, as a function of the separation between the two tracks. The horizontal line indicates the resolution for single laser tracks.

recorded with a normal cosmic trigger. The tracks reconstructed are then investigated for distortions in the area where the charge produced by the source is filling the drift volume.

The results are illustrated in figure 21. It shows the distortions caused by an ion charge which is four to five orders of magnitude more than expected in the LC TPC. For the plot on the left side a setting with large ion backdrift was chosen, while for the plot on the right side the GEMs were operated with settings to minimize the ion backdrift. This comparison is to illustrate the effect of this minimization, and the resulting reduction of the distortions is clearly visible. We are currently using as limit for the maximum allowable space charge a value estimated in the Star TDR[11], and it is clearly important to crosscheck this value. The expected background occupancy during LC TPC operation corresponds to a space charge due to primary ionization which is about three orders of magnitude below this maximum.

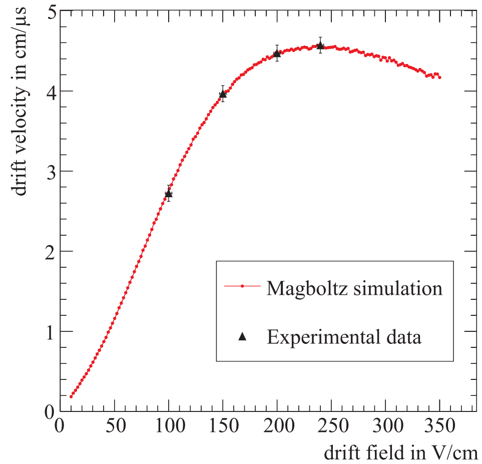


Figure 20: Drift velocity measured in the TDR gas at a fixed drift distance.

6.9 First Results from a TPC with CMOS Pixel Readout

The layout of the test chamber is shown in Figure 6. A cathode foil is fixed above an aluminum base plate by means of spacers, forming a drift gap of 15 mm. The MediPix2 readout chip is mounted on a brass pedestal and placed flush with the base plate upper plane. On top of the chip a Micromegas foil, fixed on a frame, is held in position by means of two silicon rubber strings.

A MediPix2 chip [12] [13] [14] was applied as experimental readout device. This CMOS chip contains a square matrix of 256 $\times$ 256 pixels, each with dimensions 55 $\times$ 55 μm^2. Each pixel is equipped with a low-noise preamp, discriminator, threshold DACs, a 14-bit counter and communication logic.

The MediPix2 wafers were post-processed by MESA+ [15]. The post-processing consisted of a deposition of a thin aluminum layer using lift-off lithography. The pixel pads were thus enlarged to reach a metal coverage of 80% of the anode plane. Electrical tests showed that the preamplifier functionality was unaffected by this post-processing.

The Micromegas [4] is a copper foil, thickness 5 μm, with holes of 35 μm diameter in a square pattern with 60 μm pitch

To minimize the chance of a discharge the setup is operated in a He based gas mixture, with an addition of 20% Isobutane.

As the current chip has no timing capabilities, images were taken over a fixed length of time, of typically 15-60 s, and integrating any activity which may have happened in this time interval. A picture recorded in this way is shown in figure 22. It clearly shows a cosmic muon together with a δ-electron.

With a He/Isobutane 80/20 mixture, signals were observed from ^{55}Fe events with -390 V and from cosmics with -470 V on the Micromegas and -1000 V on the drift cathode plane. A suitable selection to obtain a sample of clean cosmic events was made. In total 164 events were selected in the data. The distribution of the r.m.s. spread of hits along a track is sensitive to the diffusion constant. Data give an average value of 2.0 pixels (simulation estimates 2.4). This implies that the diffusion constant is slightly better than 220 μm per $\sqrt{\text{cm}}$. The observed number of pixels hit per mm is 1.83 on average (simulation 2.70). The number of clusters per mm is 0.52 (simulation 0.60). The average 3D track length is 16.5 mm. The number of clusters per mm agrees within 15% with the simulation, the number of electrons within 35%. Note that a 100% efficiency is assumed for the detector. Given

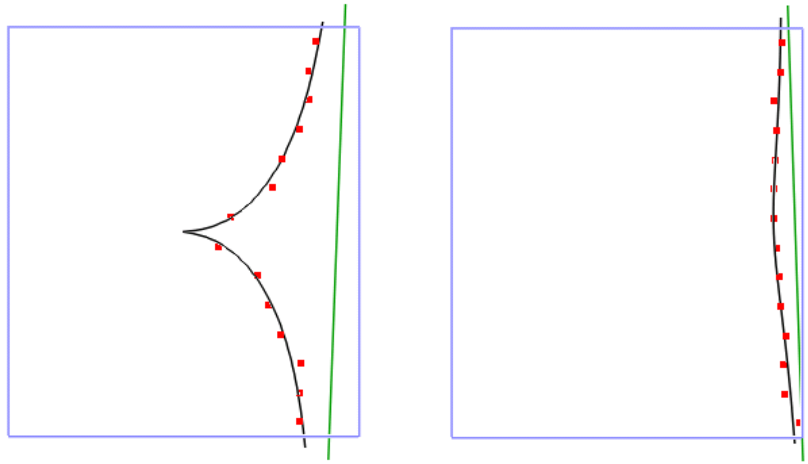


Figure 21: Distortion of tracks from cosmic ray muons with normal settings (left) and settings optimised for minimum ion backdrift (right). The charge density for these plots is about six orders of magnitude worse that expected at the ILC, and the figures are just to illustrate the improvement due to optimisation. The green line indicates the expected position of the track, if there were no distortions present. The black line is a fit to the point assuming a simple model for the distorted track.

the currently still very large uncertainty about systematic errors, the agreement between data and simulation is acceptable. Later experiments will focus on a more precise quantitative understanding of the detector.

For the future generation of chip, called $TimePixGrid$, the grid holes will be precisely centered above the pixel pads, eliminating the non-homogeneity of the efficiency. This can be achieved by integrating the Micromegas and the chip through a post-processing step. A first prototype of such an integrated chip is under construction at MESA+ and should soon become available for HV and signal tests. If successful, the process will be applied on a real Medipix wafer.

The next step is to modify the Medipix2 chip by adding a (drift) time measurement to each pixel. This seems feasible by using the existing hit counter in each pixel and let it count clock pulses. This however needs substantial funding, in order to make one or two test submits for such a modified Medipix. The funding needed is not sufficiently available at NIKHEF and a collaboration needs to be formed in a similar way as the existing Medipix Consortium, where several labs contribute to this project.

7 Future program

In this section the proposed program for the next few years is outlined. It has been developed under the assumption that the schedule for the linear collider will be approximately that proposed by the Organising Committee of the World-Wide Study on Physics and Detectors for the Linear Collider (WWSOC). The steps for the detectors should keep pace with but slightly behind the schedule for the machine as being drawn up by the Global Design Initiative (GDI), for which planning is proceeding rapidly following the ITRP technology decision. The WWSOC is thus proposing detector costing in 2005, detector CDRs in 2007, LOIs to the Global Lab around 2008 and TDRs to the Global Lab

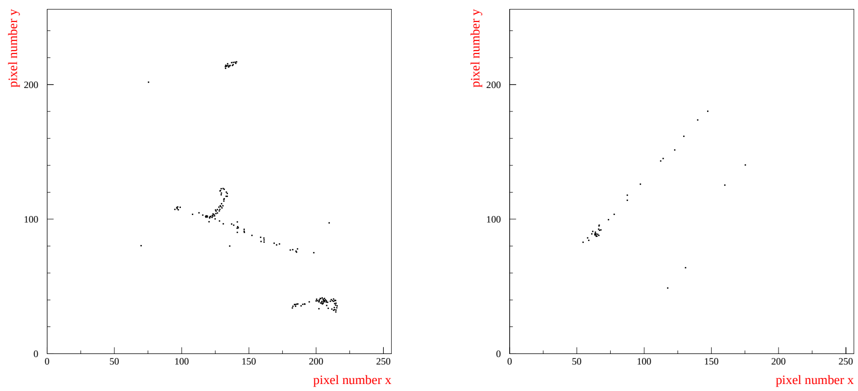


Figure 22: Left: Image recorded from the MediPix2/Micromegas prototype TPC showing a cosmic charged particle track together with a δ-electron. The total size of the image is 14.1 $\times$ 14.1 mm^2. Right: Image showing selected cosmics charged particle tracks.

around 2009. (The latter two would of course be decided by the Global Lab.) This would then be the time at which a concrete proposal for a detector has to be written. A decision on the technologies to be used should be made in 2008 at the latest. The R&D work should be planned under the assumption that the basic questions are addressed before 2008.

The next steps planned for the LC-TPC can be grouped into three phases:

1 Demonstration Phase: Finish the work on "small" prototype as outlined in the previous sections. The goal of this work is to provide a basic evaluation of the properties of a MPGD TPC and to demonstrate that the requirements outlined at the beginning of this document can be met.

2 Consolidation Phase: Design, build and operate a "larger" prototype. "Large" in this context means that the detector should be significantly larger than the current prototypes, so that first iterations of a TPC design for the LC can be tested, that larger area readout systems can be operated, and that tracks with a large number of points are available. "Large" should not be understood as approaching the size of the final detector.

3 Design Phase: Start to work on an engineering design for some of the aspects of the final detector. This work in part may overlap with the work for the design of the large prototype, but the final design can only start after the large prototype is completed.

In the following the plans will be outlined in a bit more detail.

7.1 Demonstration Phase

During the last two years work has progressed on a broad front towards demonstrating that a MPGD equipped TPC can be operated and does perform as expected. Currently data are available on the resolution, on efficiencies, and are becoming to be available on the double track resolution. In only very small setups has the theoretical limit of the performance been reached, indicating that there is still significant room for improvement. The goal of this first phase will be to finish the exploration of the available phase space, study in detail the single and double track resolution, and do this for a sensible range of gases and operating parameters. For the Si-based readout this phase will include a basic proof-of-principle of the feasibility of this readout for systems of the size of the present small prototypes.

It is expected that this phase will be finished in about one year from now.

7.2 Consolidation Phase

While the results from the first phase of this R&D will answer many of the basic questions concerning the feasibility of a MPGD TPC, only very few of the actual implementation problems are addressed. The goal of the second phase therefore is to move from the current small prototypes to a larger one, which is large enough to test a number of critical design issues of this TPC. The emphasis of this prototype will be on the development of a realistic endplate, with which the multiple MPGDs, the effects at boundaries between neighboring MPGDs, and the interface between the field-cage and the endplate can be studied. Such a larger prototype will also require a significantly more compact readout electronics, and thus provide a test bed for the development of a highly integrated TPC electronic.

It is planned to design and develop this generation of prototypes in such a way that the field cage can be equipped with different endplate designs, utilizing different gas amplification technologies, and possibly also different cathode designs. Such a modular structure would allow the efficient sharing of resources, while still allowing the independent execution of experiments by the geographically widely separated groups.

The design of this modular second generation test TPC is just starting. It is expected that significant design work will begin in about half a year. Finalizing the design and building the chamber will take between 1 and 2 years, depending on the resources available. The chamber will then be tested in a commonly organized cosmic ray and test beam experiment.

7.3 Design Phase

The results from the first two R&D phases will funnel into the final proposal of a TPC at a linear collider experiment. Towards the end of the second phase it is expected that increasing efforts will be diverted into a concrete engineering design of a TPC. The details of this phase are beyond the scope of this report and can only be defined at a later stage.

On the road towards this design the LC-TPC community will need to decide on a technology to be used for this detector and on a final list of requirements. At the moment it is expected that this decision does not need to be taken before the global laboratory has formed.

7.4 Test Beam Needs

Many of the R&D activities can be carried out using cosmic muons. Very important for the success of the program is the availability of high field test magnets, ideally for fields up to 4T and for chambers of large radii. In the absence of such magnets, large bore moderate field magnets, delivering fields around 1T, are adequate if combined with tests of small prototypes in the large-field magnets.

Commissioning and first results can be obtained based on the cosmic muons. In addition medium energy beams, e.g. the electron beam at DESY, will be very useful throughout the commissioning and first measurement phase to understand the system, make first measurements and optimise the setup. Eventually however the chamber should be tested in a hadron test beam with high rates and different types of particles. It is not yet clear where such an test experiment will take place.

Internationally a discussion has started to ensure that adequate test beam resources will be available to linear collider detector R&D projects for the next few years. While the majority of the requests for test beam come from calorimeter groups, nevertheless the tracking groups and in particular the LC-TPC is following these discussions very closely to identify a suitable test beam available in a few years time.

7.5 Funding

At the moment the LC-TPC groups obtain their funding from a number of different sources, and through a variety of review mechanisms. The largest costs are encountered in the development and building of a new readout system with a significant number of channels and for the CMOS based readout scheme. Both efforts are currently critically underfunded.

The funding situation concerning the building of the next generation prototype is tight, and a coherent design must be developed in cooperation between the groups.

8 Conclusion

The LC-TPC groups two years after the start of a concerted effort have accumulated a large body of data and experience with the operation of TPCs equipped with MPGDs. The basic feasibility of using MPGDs in a TPC could be demonstrated.

Currently the participating groups are in the process of finalizing first systematic investigations into the single point and double track resolutions. Several novel methods are under study to readout the required large number of channels, including a proposal to directly couple a CMOS pixel sensor to the readout plane of a TPC.

In the future the work will concentrate on the design, building and operation of a series of larger prototypes, to test not only the basic feasibility but also detailed engineering questions. All these should be answered before a real design for the big detector is started.

The LC-TPC groups expect that this second phase of the work will take around three years and will require substantial funding, exceeding the currently approved resources. An international effort therefore is needed to secure the needed support and to focus the available resources.

The LC-TPC groups request the DESY PRC to continue supporting its program and its quests for additional funding from the international community. The DESY group within the LC-TPC groups asks the PRC to approve its continued participation in this effort and requests adequate support to maintain its role.

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