Progress on Pixel Readout of a TPC

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Abstract

We report on progress towards a Time Projection Chamber with pixel readout in the year 2006.

1 Introduction

A Time Projection Chamber for the ILC is an attractive option for precision tracking of charged particles. The SiTPC task within the EUDET project aims at supporting the development of such a TPC by providing access to a novel charge readout technique based on charge-sensitive integrated pixel readout chips. Such readout chips have been developed in the past for the readout of Silicon Pixel Detectors both for Imaging and Particle Physics applications.

In the context of a TPC, the smallness of the available readout structure provides experimental access to the details of the charge clouds produced in the gas multiplication devices under study, Gas Electron Multipliers (GEMs) and Micromegas. Within EUDET, the goal is to provide an integrated endplate structure (or module) for a pixelized readout of GEMs and Micromegas to allow for an optimization of the readout structures.

The R&D path chosen builds on the available Medipix2 chip. Within EUDET a successor of Medipix2, the Timepix chip was developed at the CERN microelectronics workshop. In Section 2, we report on the features and the successful production of the Timepix chip. In Section 3 the development of an integrated Micromegas structure placed on a silicon carrier, the INGRID structure is described. Also progress on discharge protection of such structure through the disposal of a layer of amorphous silicon is explained. In Section 4 results on gain measurements for a Micromegas detector for a multitude of different gas mixtures is shown. In Section 5 tests of a triple-GEM detector with Medipix2 and Timepix readout are described. Finally, in Section 6, progress on detailed simulations of such devices is reported.

2 Development of the Timepix Chip

The Timepix chip is an evolution from the Medipix2 chip which allows for measurement of arrival time, energy measurement and single photon counting. The Timepix chip has the same size, readout architecture and floorplan as the Medipix2 chip allowing almost a full backward compatibility with the existing Medipix2 readout systems. These readout systems must be only updated to provide an external reference clock signal (*Ref_Clk*) to the chip. This external clock is used to generate the pixel clock signal which increments the pixel counter depending on the selected pixel configuration mode.

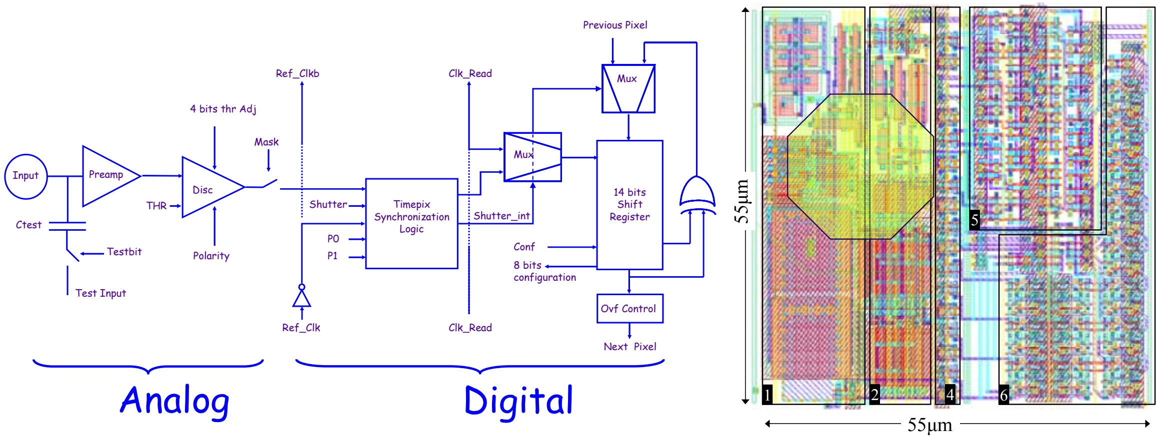

Figure 1: Timepix pixel cell schematic and layout

A schematic of the Timepix pixel can be seen in Fig. 1. The pixel size is 55 x 55 μm^2 and contains:

- A charge amplifier with DC leakage current compensation
- A threshold discriminator with 4-bit fine threshold adjustment and hysteresis output with polarity selector
- Timepix Synchronization logic (TSL): This logic synchronizes the *Ref_Clk* with the *Shutter* and the discriminator output to generate the counting clock depending on the selected pixel mode set by the P0, P1 and Mask bits. The 4 different pixel working modes are:
    - Masked: The pixel counter is never incremented
    - Single photon counting mode: Each hit above threshold increments the counter by 1
    - Analog mode: The counter is incremented continuously while the discriminator is over threshold
    - Arrival Time mode: The counter is incremented from the moment the discriminator fires until the global Shutter signal is turned of.
- A 14-bit shift register that can work as a counter with overflow control up to 11810 counts or as a shift register to read out the data from the matrix.

The chip is arranged as a matrix of 256 x 256 pixels of 55 x 55 μm^2 resulting in a detection area of 1.98 cm^2 which represents 87% of the entire chip area. The periphery contains a bandgap circuitry, 13 DACs and the IO control logic. Both the analog and digital circuitry have been designed to operate with independent 2.2V power supplies with a total analog static power consumption of about 420 mW, and a digital static power consumption depending on the applied *Ref_Clk* frequency (440mW when counting and at 100MHz). The chip contains around 36 million transistors.

Chip was submitted to foundry at the beginning of July and 12 wafers arrived at CERN 2nd week of September. Some modifications had to be done in the Medipix readout system (~1 week) to make it compatible with the Timepix chip: A new "Timepix-Medisoft" version of the software and a MUROS2 firmware update. Preliminary Timepix characterization has been done on-wafer using the Medipix2 probe card in the DSF clean room facility at CERN. A version of the Pixelman software has been provided by the Medipix2 partners in CTU, Prague (T. Holy, J. Jakubek, S. Pospisil).

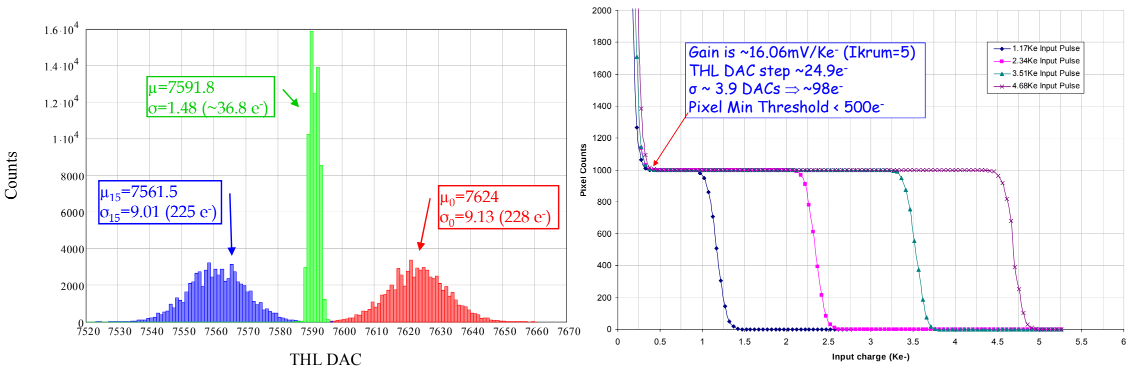

Figure 2: Left: Timepix threshold equalization. Without equalization (blue and read) and after equalization (green). Right: Pixel S-curve for 4 different input charges using the single photon counting mode
Timepix

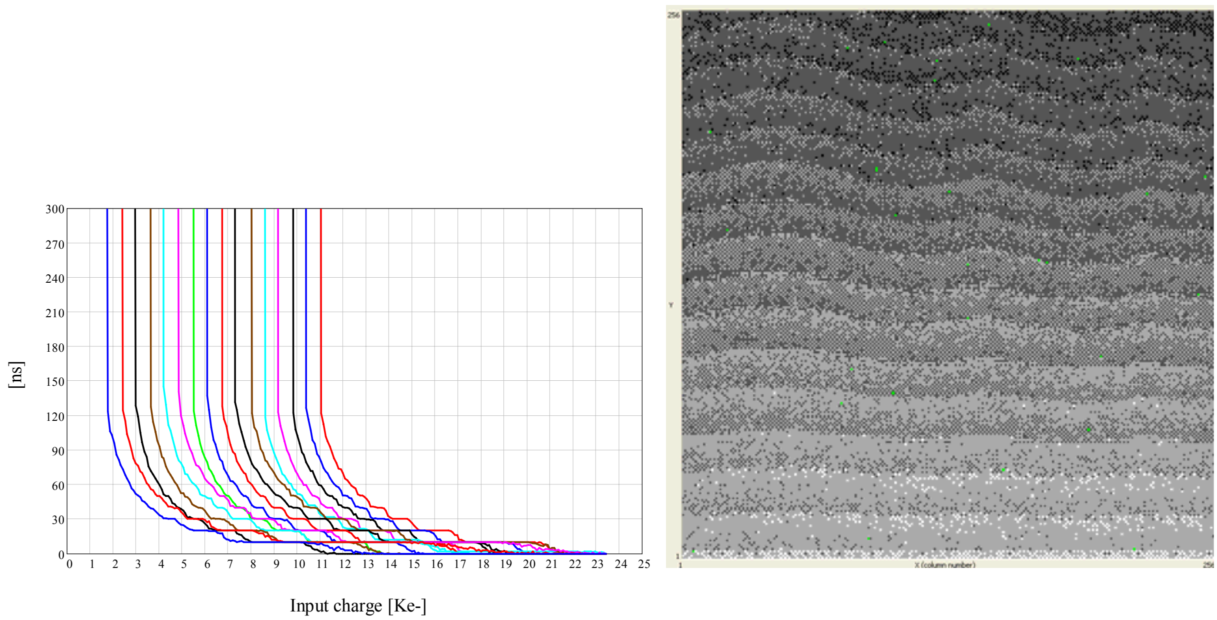

Figure 3: Left: Timepix pixel time walk for different thresholds. Right: Arrival time measurement of a 30Ke⁻ input pulse at a threshold of ~1Ke⁻. Measured time is 1019.5 ±1.5 counts or 14.359 µs ± 21.12 ns.
Timepix

Fig. 2 on the left shows the Timepix chip equalization results using the noise floor to find each pixel threshold. The threshold distribution after equalization is ~35e⁻rms. Fig. 2 on the right shows 4 different S-curves generated with the external test pulser are used to compute a pixel noise of ~100e⁻ rms and a pixel gain of ~16mV/Ke⁻. Fig. 3 on the left shows that the arrival time mode at pixel level has constant time-walk of ~60ns for different thresholds from an input charge double the threshold set to an infinite injected charge. On the right of Fig. 3 is shown the full matrix arrival time dispersion of a 30Ke⁻ input pulse at a threshold of ~1Ke⁻.

3 Progress on INGRIDs and Discharge Protection

The concept of pixel readout of gas-filled detectors was validated in 2004 by combining a Micromegas amplification grid with a Medipix2 CMOS chip as a pixel segmented anode [1]. The fine granularity offered by the pixel matrix results in improved spatial resolution and 2-track separation compared to a ‘traditional’ pad readout. Furthermore, the good single (primary) electron efficiency (>90%) can improve the energy loss measurement through a cluster counting technique.

As a possible solution for the fabrication of larger pixelised Micro Pattern Gas Detector (MPGD) elements, the NIKHEF group proposed the integration of the Micromegas amplification grid and the CMOS readout chip (Ingrid) by means of wafer post-processing technology: the structure of a thin (1 μm) Aluminium grid is fabricated on top of an array of insulating (SU8) pillars of typically 50 μm height, which stand on the CMOS chip. This structure thus forms a `monolithic’ detection and readout device. This work was done in close collaboration with the MESA+ institute of the University of Twente, The Netherlands. Results from a a first working Ingrid were published in 2006 [2].

Much better control of the production process was achieved in the last year and several Ingrids of different geometry, shape and pitch of the grid holes, and multiplication gap thickness (pillar height), see Fig. 4, were produced and tested with various gas mixtures. The gas multiplication gain was shown to drop with increased optical transparency of the grid. The energy resolution as a function of the gain was found to be almost independent of the grid geometry. For a given gas mixture, best energy resolution was reached at a gas gain of around 5000. The degradation of the resolution at gains above 5000 is believed to be due to insufficient UV quenching. Measurements of the gas gain for different gap thicknesses were done for Argon and Helium based mixtures with either Isobutane or Carbon-dioxide as quenchers. They indicate that a maximum in the gas gain is reached for a gap thickness around 50 μm (at fixed grid voltage), in agreement with expectations from model calculations.

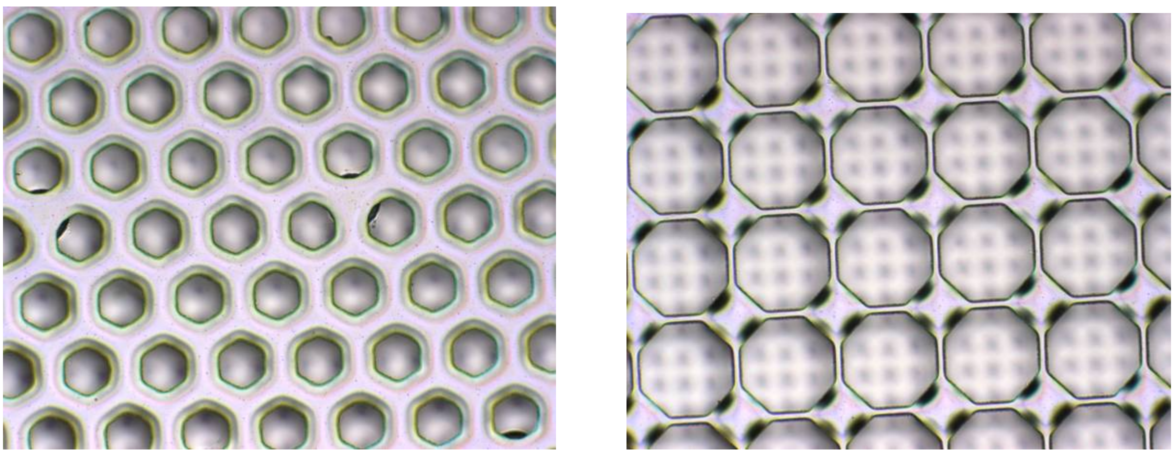

Figure 4: Photographs of different INGRID structures

Unlike setups where a (triple-)GEM structure is used as gas multiplier, the electric field just above the CMOS readout chip in our setup with a Micromegas (or Ingrid) multiplication stage is about an order of magnitude higher. This increases the probability of discharges, damaging irreversibly the CMOS chip. Two possible solutions are being investigated:

1) use of a highly resistive layer of 4 μm of amorphous Silicon (aSi) with a resistivity of ~ 10^{11} Ω.cm covering the chip. The expected effect is a limitation of the current of large avalanches (e.g. discharges). First tests with and without such a protection layer deposited on a non-pixelated anode showed that in a 80/20 Ar/Isobutane gas mixture the “unprotected” detector gain could not be raised above about 20,000 before the occurrence of discharges, while a “protected” detector could reach gains of a few millions. Both “protected” and “unprotected” detectors showed about equal signals from minimum ionizing particles. After these encouraging results, in a next step, few Medipix2 and TimePix chips are also being covered with such protection layers and first results are expected early 2007. Just before the end of 2006, a first “protected” TimePix chip with a Micromegas as gas gain grid became operational in a small drift chamber (15 mm drift gap) filled with a 80/20 He/Isobutane gas mixture. First examples of observed charged particle tracks are shown in Figure 5. At the time of writing this TimePix chamber has been under HV for more than two weeks, without damaging the chip.

2) a second possibility to protect the readout chip is to fabricate a 2-stage Ingrid structure using the same wafer post-processing technique. Two layers of metallic grids and insulating pillars are superposed. The “top” gap ca then be used as main amplification grid, while the “lower” gap just above the CMOS chip can be operated at a much lower field strength, sufficient to extract the avalanche charge created in the “top” gap onto the anode. A first fabrication attempt of such a double-grid structure was successful. Full prototype structures will soon become available for tests in a gas detector.

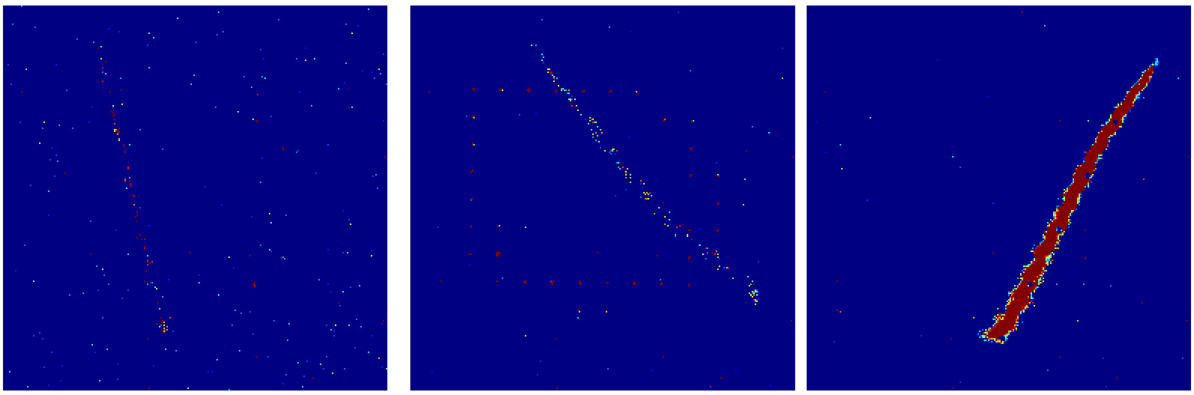

Figure 5: Micromegas + Timepix events

4 Gain Measurements for a Micromegas TPC

Micromegas is a parallel-plate micropattern gaseous detector using an amplification gap of a few tens microns. The electron multiplication factor and the energy resolution depend mainly on the gap, the electric field and the gas mixture [3, 4, 5].

The gain of such a detector has been measured as a function of the amplification electric field for nearly 50 gas mixtures and compared with simulations showing thus their limitations. For each gas the charge deposited by 5.9 keV X-rays is used.
Using the same detector systematic measurements have been carried out with double mixtures and triple mixtures of gases (Ar, Ne, CO_2, CH_4, C_2H_6, Iso-C_4H_{10}, CF_4, ...) at various concentrations.

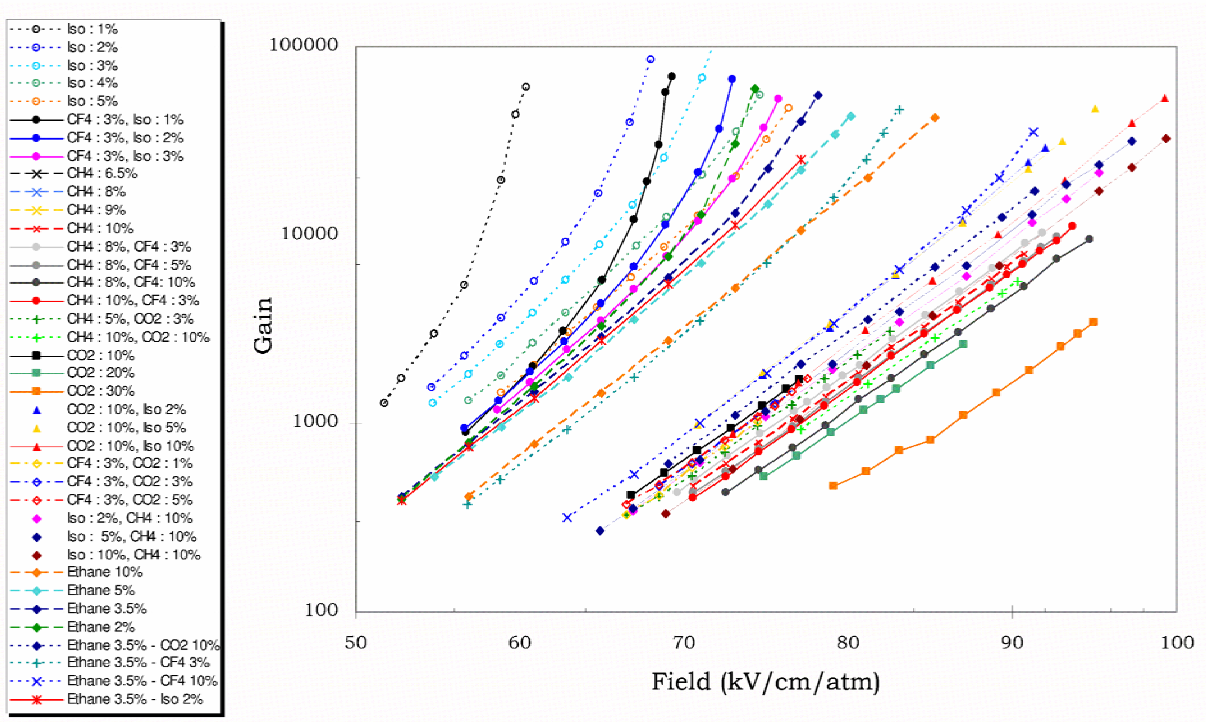

Figure 6: Gain curves vs. amplification field measured by a Micromegas detector using gas mixtures containing Argon and a few percent of CO_2, CH_4, C_2H_6, Iso-C_4H_{10}, and CF4.

The detector is a transparent plastic box of 23 cm × 23 cm × 8 cm size including a standard Micromegas mesh of 10 cm × 10 cm size. Two kind of sources have been used: the ^{55}Fe radioactive source providing a 5.9 keV energy line and a x-rays source providing by the Amptek Cool-X X-Ray Generator[1] (line at 8.1 keV).

Fig. 6 shows the gain curves as a function of the amplification field E for many gas mixtures. Three groups of curves can be distinguished. The first group is formed by the Iso-C_4H_{10} mixture which yields the higher gains, up to 10^5 (50 kV/cm < E < 70 kV/cm). The second group, mainly composed by cold gases (CH_4, CO_2), have a maximum gain up to a few 10^4 (70 kV/cm < E < 100 kV/cm). Finally, between those two families (60 kV/cm < E < 80 kV/cm) is the C_2H_6 gas mixtures.
The gain of such a detector has been measured as a function of the amplification electric field for nearly 50 gas mixtures and compared with simulations showing thus their limitations. For each gas the charge deposited by 5.9 keV X-rays is used.

It appears that the more the quencher contains hydrogen the higher the maximum gain is. The (argon+isobutane) mixture shows a significant deviation from the exponential gain at high fields. We believe that it is due to photons from the avalanche which re-ionize the medium, increasing the gain.

Adding CF_4 in a mixture translates this curve to the right side and keeping exactly the same shape which means that it gives us less gain at the same electric field.

The GARFIELD software has been used to simulate the gain curves (it contains the Magboltz program, by S. Biagi, which estimates the gain). The comparisons are shown Fig. 7 as a function of the electric field E for two gas mixtures (Ar/CH_4 and $Ar/Iso\text{-}C_2H_{10}$) at various percentages.

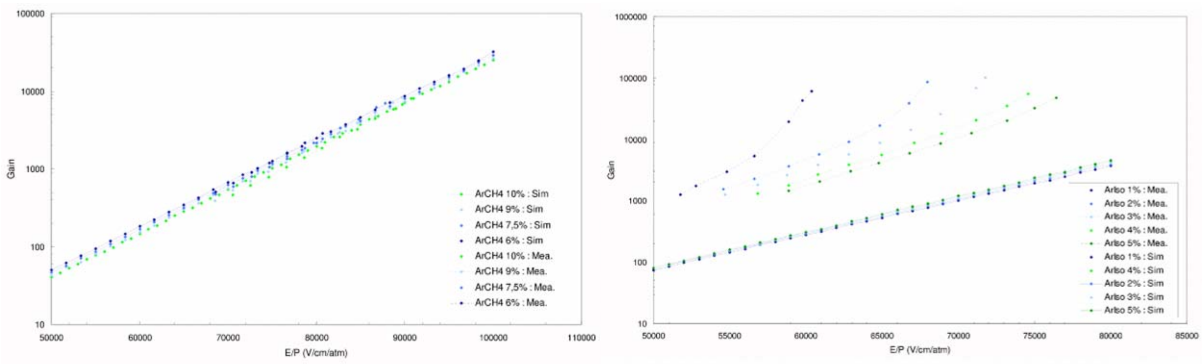

Figure 7: Simulated and measured gain as a function of the electric fields E for Ar/CH_4 (left) and Ar/C_4H_{10} (right) at several percentages.

The next stage is to build a test detector using both technologies Micromegas and a Medipix2 chip ([6]) or its time-sensitive version TimePix. To this end we designed a small chamber sitting above a chip, i.e. a SiTPC with a 6cm drift length. The parallepipedic (2 cm × 2 cm × 6 cm) field cage is applied on a Micromegas mesh support. Two mylar windows, one on its side and one on its top, provide the transparency to β and X-ray sources. A careful choice of the materials is under study for this chamber.

Good progress has been achieved this year on the understanding of the gas gain properties using a Micromegas detector and these studies will continue. The forthcoming measurements with a small chamber using Micromegas and a Medipix2/TimePix readout chip together will allow reproducing the early (2004) measurements. It will even allow new and precise measurement and hopefully will demonstrate the possibility of integrating it to the ILC Large Prototype.

5 Pixel-Readout of a Triple-GEM Detector

The activities in Freiburg (and in Bonn since September 2006) are centered around a proof-of-principle device [7] to detect the charge clouds produced in a stack of three Gas Electron Multiplier Foils (GEMs) with the Medixpix2 and Timepix pixel readout chips.

The device consists of a gas-tight box containing both the detector and the frontend readout electronics. The detector itself covers a sensitive area of 10x10 cm^2. The depth of the drift region is 6 mm, followed by the charged amplification region with two transfer gaps of 2 mm depth each and a 1 mm induction gap. The readout plane consists of 5x5 metalized readout pads of 2x2 cm^2 area, one of which is replaced by the pixel chip. Standard CERN-produced

GEM foils (50 µm thickness, 140 µm pitch, 70 µm hole diameter) are used. The 24 pads which are used for monitoring and trigger are readout by discrete L3 muon preamplifier-discriminator electronics. The Medipix2/Timepix chip is readout by the MUROS2 readout system using MediSoft4 software.

The detector was operated mainly in Ar/CO_2 (70:30) and He/CO_2 (70:30) gas mixtures. Typical field configurations for Ar/CO_2 were $E_{drift}/E_{transfer}/E_{induction}$ = 1.1/3.2/4.2 kV/cm with GEM voltages of $\Delta V_{GEM1} = \Delta V_{GEM2}$ = 404 V. The Medipix chip was operated at a threshold of approximately 990 electrons with an uncertainty of 140 electrons obtained from charge injection at the amplifier input.

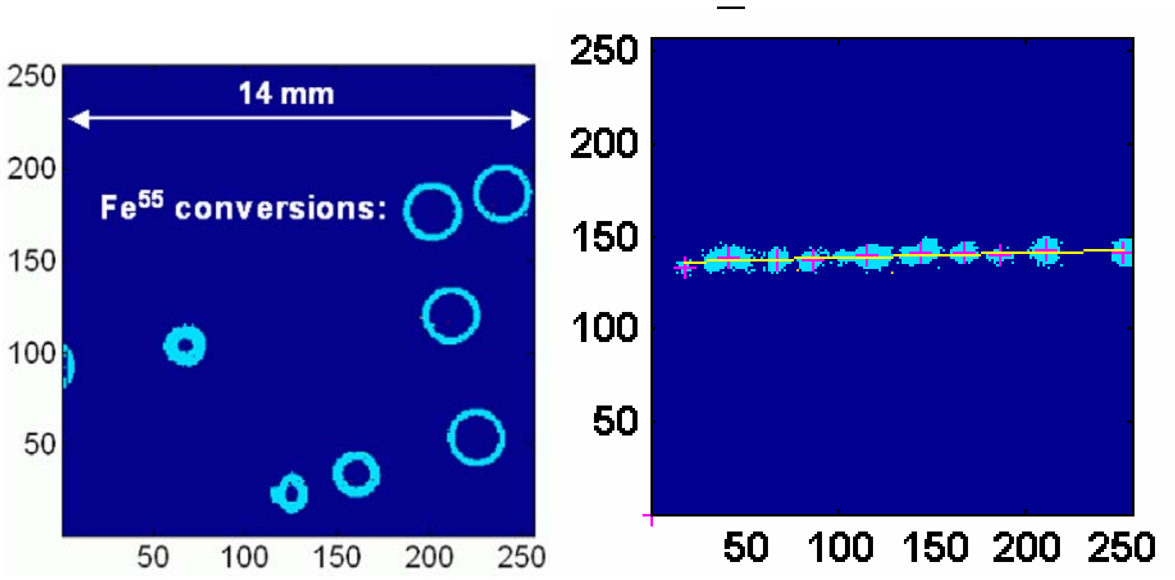

Figure 8: Left: Recording of charge clouds produced in the Triple-GEM-Detector from ^{55}Fe photon conversions in dual threshold mode of Medipix2. Right: Recorded charge clusters along the track of a 5 GeV electron at the DESY testbeam shown together with a straight line fit.

The detector was tested using gamma rays from a ^{55}Fe source, up to 3.54 MeV electrons from the β-decay of ^{106}Ru and up to 5 GeV electrons at the testbeam area at DESY. Typical signals from ^{55}Fe X-rays recorded in the dual threshold mode of Medipix2 are shown in Fig. 8 (left). From the distribution of the inner and outer radii of the charge clusters an absolute estimate of the total cluster was inferred under the simplifying assumption of a triangular shape of the charge distribution. With this method both the 5.9 keV photopeak and the Argon escape peak could be identified in the spectrum. Using this method and the fact that the total deposited charge of 5.9 keV photons is 220 electrons, the gain of the 3-GEM-structure was estimated to be $6x10^4$ at ΔV_{GEM} = 404 V and $2x10^5$ for ΔV_{GEM} = 428 V.

Tracks from a ^{106}Ru β source were observed and the point resolution was determined with various methods. Effects from multiple scattering in the drift region were clearly observed. Point resolutions of approximately 55 (50) µm were measured in Ar/CO_2 (He/CO_2) averaged over tracks in the whole drift region of 6 mm.

The detector was then operated at DESY in a testbeam of ~5 GeV electrons. The electron tracks positions were determined by external Si-Strip detector planes in front of and behind the 3-GEM detector. Approximately 100.000 tracks have been recorded and analysis is still underway. Preliminary analysis shows that the point resolutions are consistent with those obtained from the β-source after multiple-scattering correction. The diffusion of the primary electron clusters along their drift path was clearly observed by correlating the event-wise track residuals with the position of the track determined from the Si strip telescope. Extrapolating the point resolution to zero drift length, the intrinsic point resolution was determined as σ_0 = 31±5 (29±5) μm for Ar/CO_2 (He/CO_2) from a preliminary analysis.

Shortly after the Munich annual EUDET meeting, the 3-GEM detector was equipped with a Timepix chip replacing the Medipix chip and operated in the same setup at the DESY testbeam. First results are very encouraging: the Timepix could be operated at thresholds similar or lower than the previous Medipix2 chip with a minimal amount of noise hits. In Fig. 9 an electron track with a clearly visible delta electron recorded in time-over-threshold (TOT) mode is shown. The colours denote the amount of charge deposited on a pixel.

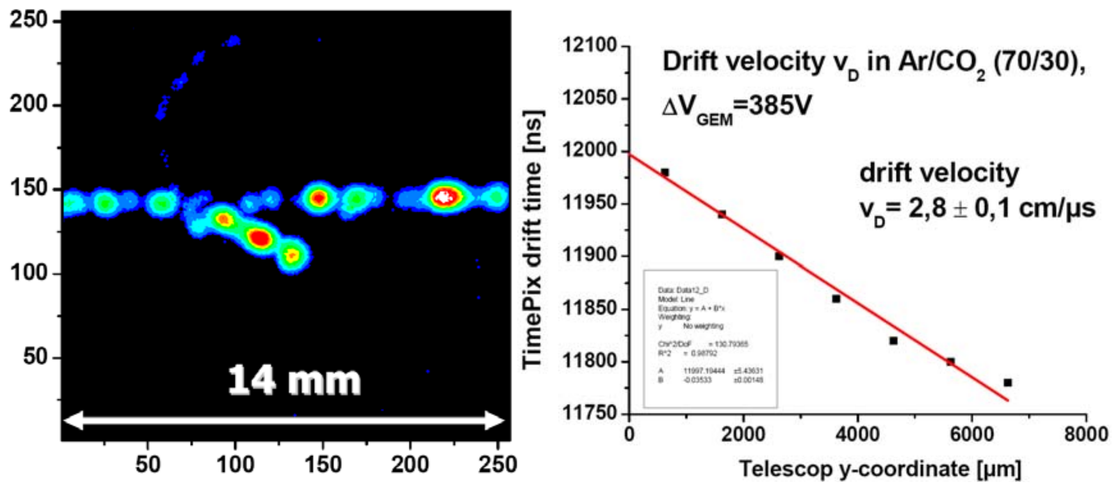

Figure 9: Left: Electron track with a δ-electron at the DESY testbeam recorded with Timepix in TOT mode. Right: Correlation of the vertical track position determined from the Si-strip telescope with the average drift time measured in TimePix TIME mode.

From the correlation between the vertical track coordinate measured with the Si strip telescope and the drift time measured in Timepix TIME mode, a preliminary determination of the drift velocity in Ar/CO_2 could be achieved. The measurement is in agreement with simulation.

In summary, the operation of a 3-GEM detector with pixelized readout has been shown to be feasible. The features of the observed charge clusters whose size is determined by diffusion in the gas amplification region are understood qualitatively. Detailed quantitative analysis is underway. Preliminary measurements of point resolution, gas amplification, diffusion coefficients, and drift velocity are very encouraging.

6 Progress on Simulation

The DESY testbeam set-up also has been simulated using the CLUSCO simulation tool that has been developed in particular to study performance characteristics of Micro Pattern Gas Detectors (MPGD) with MediPix and TimePix read-out.

CLUSCO is generating ionization clusters/electrons including creation of δ-electrons along a charged track using the HEED cluster generator (I. Smirnov). Electrons are then drifted towards the 3-GEM structure using gas parameters obtained from MAGBOLTZ (S. Biagi). Path of the electrons through the GEM holes is approximated using simple geometric transformations without detailed E-field maps. Electrons entering the 3-GEM structure are subject of a 3-step gas amplification process, each step following an exponential gas gain distribution.

All electrons created in the gas amplification process are then drifted towards the MediPix or TimePix device and are collected on the individual pixels. For a 5 GeV electron track typically 10^7 electrons are generated in total by gas amplification and have to be handled. In the final digitization step, noise of 100 e^- ENC is generated and a detection threshold of 1000 ± 100 e^- is applied.

The simulated pixel data are processed further by application of a simple cluster finding algorithm based on a search for simply connected areas. Each simply connected area is considered as an approximation of the initially generated primary ionization cluster. The simple algorithm does not allow resolving two or more close-by overlapping clusters. In case of the MediPix, no pixel amplitude or TOT information is available and not used by the cluster finding algorithm.

Various gas mixtures and 3-GEM set-ups used in the DESY testbeam have been simulated. Cluster finding efficiencies of ~15% for Ar/CO_2 and of ~35% for He/CO_2 were found. However, the primary ionization density for He/CO_2 is significantly lower compared to Ar/CO_2 and thus, compensating the higher efficiency. The simulation indicates that the reconstructed cluster density is about 5 to 6 clusters/cm for both mixtures and mainly limited by the size of the clusters due to diffusion in the 3-GEM structure.

A point resolution of 46 μm in Ar/CO_2 averaged over tracks in the whole drift region of 6 mm is obtained, the agreement with data was found to be better than 10%. The point resolution is derived from the cluster positions y_1,y_2,y_3 of three neighboured clusters by $\sigma_{point} = \sqrt{2/3} \cdot \sigma[(y_1+y_3)/2 - y_2]$. From the residuals of an unbiased straight line fit to the reconstructed cluster positions of the tracks a resolution of 54 μm has been obtained.

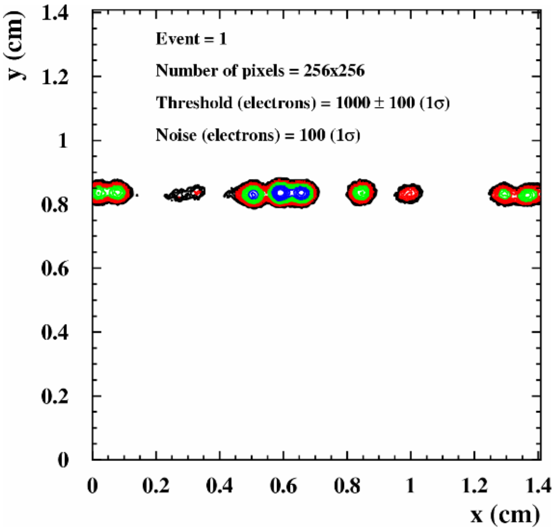

Figure 10: Simulated pixel data from a 5 GeV electron track. The pixel amplitude (number of collected electrons per pixel) is colour coded for illustration. However, this information has not been used by the cluster finding algorithm (MediPix mode).

7 Summary

The first reporting period (2006) for the SiTPC task has been extremely successful. The most important milestone and deliverable, i.e. the development, production and successful test of the TimePix chip have been achieved in the second half of 2006. Initial electronic characterization tests of the chip show that it behaves according to specifications. The yield of good chips on a wafer is very satisfactory (typically 70-80%). The TimePix chip could even be tested during a few days of beam test at DESY with the Freiburg test chamber, well ahead in time of the next milestone, which was foreseen for the end of the first quarter of 2007. Large samples of track data from the 5 GeV electron beam have been recorded and are now being analysed in detail. Just before the end of the year, also first tracks from cosmics and radioactive source were observed in the NIKHEF setup of a "protected" TimePix + Micromegas.

In parallel, significant progress was made in understanding the data recorded with Medipix2 chips (comparison with expectations from simulations for the spatial resolution and energy loss through cluster counting), with the construction of integrated gas multiplication grids (Ingrids) and promising first results on two alternatives for a better protection against high voltage discharges were obtained. Also an extensive study of gas properties (measurements and comparison with model expectations) was done for a large number of gas mixtures.

Acknowledgement

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