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The EUDET High Resolution Pixel Telescope – Towards the Final Telescope

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Abstract

A high resolution ($\sigma < 3\mu$m) beam telescope based on pixel sensors has been developed within the EUDET collaboration, a coordinated detector R&D programme for a future international linear collider. The telescope consists of up to six sensor planes and can be operated inside a solenoidal magnetic field of up to 1.2 T. A general purpose cooling, positioning and readout infrastructure is available. A flexible data acquisition is available for the telescope and the system is equipped with all required infrastructure. Since the first installation of a demonstrator telescope in 2007, it has been extensively tested and used by various detector R&D groups. The telescope and its performance as well as the future upgrade to a sensor technology with a full binary readout and data sparsification will be described in this work.

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1 Introduction

A linear electron-positron collider operated at a centre-of-mass energy of 500 GeV or more is the next great international project in high energy physics. The EUDET project [1] which is supported by the EU in the 6th Framework Programme (FP6 [2]) aims to provide infrastructures for the R&D of detector technologies toward the international linear collider. Within the EUDET project the joint research activity 1 (JRA1) works on the improvement of test beam infrastructures. For this purpose a high resolution pixel telescope is developed. The design goals include a high position resolution ($\sigma < 3.0$ μm) and a readout rate of ~1 kHz. Additionally, the telescope can be operated in a 1.2 T solenoid magnet (PCMAG).
The construction of the telescope is performed in two steps. In June 2007 the so-called demonstrator telescope was installed for the first time. After an initial operation at the electron beam at DESY, the demonstrator was transported to CERN and the performance was studied using 180 GeV hadrons at the SPS [3]. The first successful integration of a Device Under Test (DUT) happened in September 2007 [4], and the demonstrator telescope has been used by various groups continuously. The existing telescope will be upgraded to its final version beginning of 2009. The upgrade will include new pixel sensors with a bigger surface, improved resolution, digital readout and on-chip data sparsification. The data acquisition hardware and software will be upgraded to higher readout speeds and data transfer rates. The final telescope will be available to the community at least till end of 2009, and more likely till end of 2010 (EU contract amendment still pending).

2 The Demonstrator Telescope

A general purpose beam telescope has to fulfil different requirements: It needs to be used by a wide range of R&D applications and quite different devices under test (DUT), from small (a few millimetres) to large (up to one meter) size. Depending on the project and on the size of the device the requirements as to precision and coverage are quite different. Still, the system should be easy to use so that a high efficiency in the use of the facility can be achieved.
The resolution of the telescope needs to be high enough to characterise ILC pixel technologies (3 μm or better), even at limited test beam energies, like e.g. at DESY (1-6 GeV electrons).The mechanical setup should allow for a wide range of different configurations from a very compact one useful for pixel sensors to a two-arm layout with sufficient space in between the arms to accommodate TPC or calorimeter prototypes. The lateral dimensions of the active area should be large enough to cover high precision pixel devices without mechanical movement of the device under test, bigger DUTs will have to use mechanical actuators. The speed of the device should allow to take full advantage of the beam rates and hence should be able to operate at readout rates of up to 1000 frames per second.

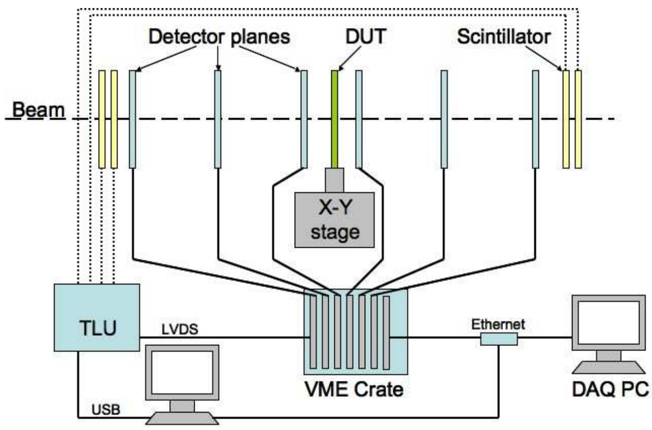

Figure 1: Sketch of the ingredients for the demonstrator telescope.

Finally, the overall setup of the telescope should be flexible enough to make it transportable in order to use it at other beam lines outside of DESY, e. g. at higher energy hadron beam lines.
As a first prototype, the demonstrator telescope has been built. The key features of the telescope are shown in Figure 1: The telescope consists of two separate arms of sensors (up to three per arm), able to 'sandwich' different DUTs. The sensors are readout by dedicated readout boards in a VME crate. For triggering, scintillators with different sizes are fixed to the telescope arms. These are controlled by a trigger logic unit (TLU). Data from the VME crate and the TLU is then collected by a central data acquisition PC.

2.1 The Sensors

The MimoTEL sensor (Figure 2) used for the demonstrator telescope was developed by the CNRS-IHPC institute in Strasbourg, France. It is a Monolithic Active Pixel Sensor (MAPS) produced in the AMS 0.35 OPTO process. Four sub-arrays of 64x256 pixels are read in parallel. With a pixel pitch of 30x30 μm^2 this results in a sensor size of 7.7x7.7 cm^2. The MimoTEL has low noise of about 15 electrons at room temperature, a signal to noise ratio above twenty and a hit efficiency of 99.9%. It achieves a single point resolution of about 3.3 μm with hadrons [?].
A high resolution sensor (HRT) with a pitch of 10 μm and 512x512 pixels can be located close to the DUT to achieve single point resolutions of $\sim$1 μm.

2.2 The Telescope Mechanics

Figure 3 shows a sketch of the sensor box mechanics. Each box contains up to 3 sensor planes on an optical bench with integrated cooling. The distance between the sensor planes can be adjusted according to the needs of the user (long arm or short arm configurations) and the boxes can be as close as a few centimetres (for small DUTs) or up to 0.5 meters apart (for bigger detectors).

Figure 2: The MimoTEL sensor and the high resolution sensor HRT (called Imager10μ here) on the wafer layout.

If needed, the DUT can be positioned on an optional XYϕ table for scanning and rotation.

2.3 The Data Acquisition System

Dedicated hardware and software has been developed for the data acquisition system of the telescope (see again Figure 1):
All data from the sensors is transferred via front end boards to an intermediate readout EUDET Data Reduction Board (EUDRB, [5]). The EUDRB board allows to perform the first steps of the data processing online. Two I/O busses are supported: For the telescope the VME64x bus is used to allow high speed data transfer and synchronous operation with other devices while an USB2.0 interface is foreseen for standalone testing. A mother/daughter board scheme has been followed to maximise the flexibility. All computing and memory elements are located on the motherboard while the sensor

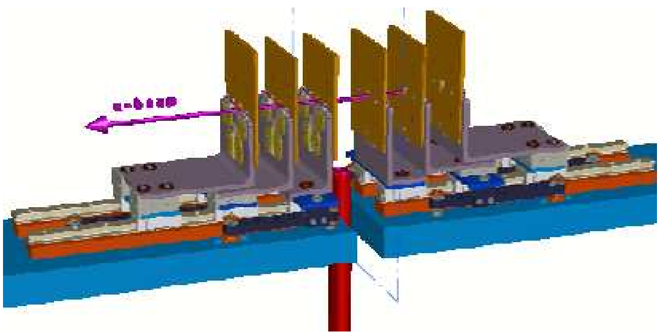

Figure 3: The Telescope Mechanics.

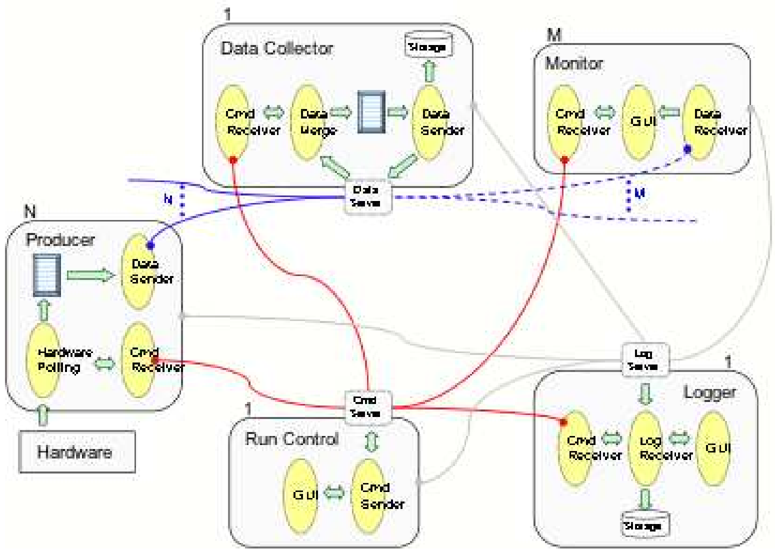

Figure 4: The EUDAQ software scheme.

specific components have been implemented on removable and interchangeable daughter cards, thus allowing a later update to other sensor technologies. Two modes of operation have been implemented in the EUDRB firmware:

- Transparent mode: All pixel signals are transferred without further data processing. This mode is important for debugging and for the characterisation of the telescope sensors itself.
- Zero suppressed mode (ZS): The correlated double sampling (CDS) is performed online and only the signals and addresses of pixels above a certain user-defined threshold are transferred. This mode is intended for data taking at high rates keeping the output files reasonably small.

The output of the EUDRB boards is collected by a MVME6100 single board computer which is located in the same VME64x crate. Finally, the data are send to the main DAQ PC using gigabit Ethernet. This computer can also collect the information from the device under test (DUT).
Another important component of the DAQ system is the trigger logic unit (TLU, [6]). It is considered as the replacement of a NIM crate and can generate any coincidence or anti coincidence of four trigger scintillators. Six LVDS and two TTL interfaces are provided. Furthermore, the TLU generates event numbers and time stamps. It is connected by USB2.0 to a control PC running the Linux operating system that is in turn connected to the main DAQ PC through gigabit Ethernet.
To control the different tasks, a custom DAQ system (EUDAQ, [7]) has been implemented in C+++. Several producer tasks communicate with a global run control using sockets (see Figure 4). These producer tasks connect to the hardware of the beam telescope, to the TLU and eventually to the DUT. Data from all producers is sent to the

central data collector and can be monitored by several processes. An online monitor based on the ROOT framework showing online data quality monitoring histograms as well as a process to collect log messages are available. EUDAQ runs on MacOS, Linux and Windows using cygwin.

2.4 User Integration

Different scenarios for the integration of the DUT in the DAQ system of the EUDET pixel telescope are possible:

- Integration at hardware level: In this case the user has to provide a hardware interface able to read out the telescope sensors and the DUT. This approach is supported by the EUDRB boards, but is only feasible for some dedicated DUTs.
- Integration at data level: Both, the DUT and the telescope use their own dedicated DAQ hardware and software. The data streams are combined online by inter process communication. In this scenario the synchronisation and the configuration during the start-up might be difficult.
- Integration at trigger level: This default scenario was chosen by most users so far, because it is easy to implement and relatively safe. Different hardware and software are used for the telescope and the DUT. The synchronisation is done using the trigger, busy and reset logic provided by the TLU. To protect against slippage of event numbers between the telescope and the DUT, the event number provided by the TLU can be optionally read by the DUT via an advanced data handshake on the LVDS trigger line.
- Integration at DAQ software level: The user provides own DAQ hardware to read out the DUT, but the data are treated by a common DAQ software. In case EUDAQ is used as the common DAQ system, a producer to read out the DUT needs to be implemented. This approach offers the biggest benefits and has been followed successfully by a few users already.

2.5 The Offline Analysis Package

For the offline reconstruction of track positions in the DUT the software package EU-Telescope has been developed which is implemented as a set of Marlin processors [8]. This design allows to integrate the DUT data at different steps of the analysis chain. Furthermore, the package is prepared to be executed on the Grid to allow a fast processing of large datasets. Figure 5 summarises the structure of the online analysis package. Each step in the analysis procedure is implemented in a separate Marlin processor. It is possible to run each processor separately or to execute the whole analysis chain by a single command. In the first step the data is converted from a native format used by the EUDAQ software to the LCIO format. Afterwards a pedestal correction is applied and clusters are searched for. It is possible to improve the reconstructed cluster positions

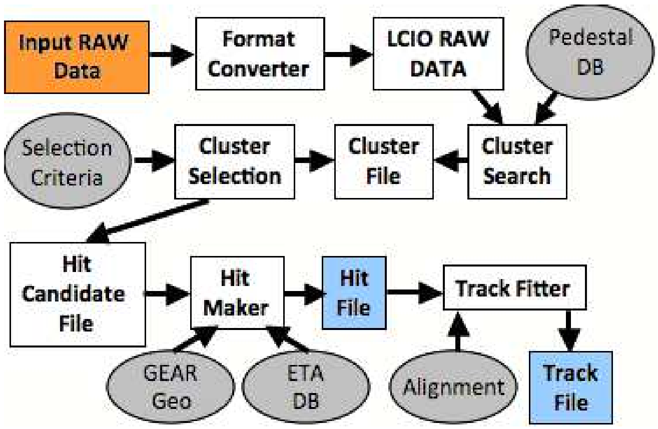

Figure 5: Typical data flow in the offline analysis package EUTelescope.

using the fit algorithm. Clusters are accordingly transformed into hits in the telescope frame of reference. The alignment procedure is based on the Millepede II package and uses full tracks in a simultaneous fit to derive the alignment parameters. Finally, tracks are are fitted using the hits after the alignment constants have been applied. The result of the track fit can be saved in a ROOT file if needed by the user of the telescope.

3 Test Beam Results from the Campaign 2007 and 2008

Since Summer 2007, the demonstrator has been available. As a first exercise, the telescope performance has been evaluated stand-alone and soon after, it has been used successfully by first users. Initially, the demonstrator was put into the DESY test beam (3 and 6 GeV electrons) and then at a CERN test beam with 180 GeV hadrons.

3.1 Telescope Performance

First, the telescope sensors were characterised with minimum ionising particles. In the setup at CERN two different types of MimoTEL sensors have been used, one kind with a 14 μm thick epitaxial layer and another version had 20 μm thick epitaxial layers. Table 1 shows the signals in ADC counts and the signal-to-noise ratios for seed pixels and for clusters consisting of 3x3 pixels.
Independent of the thickness of the epitaxial layer, the same amount of charge is collected in the seed pixels. The lower signal-to-noise ratio of sensor 3 was caused by a higher pixel noise. Our investigations found a problem in the used readout hardware and after fixing it, sensor 3 showed similar performance as the other sensors. In the sensors with thicker epitaxial layers more charge is collected in clusters of 3x3 pixels. This indicates a greater signal production but also a larger charge spread in these sensors compared to the sensors with a 14 μm epitaxial layer. For both sensor types the mean cluster size is around 8 pixels if a threshold of 2.5 times the pixel noise is applied.

Table 1: Signals in ADC counts and signal to noise ratios for seed pixels and 3x3 clusters in the individual planes measured with the setup used at CERN in September 2007. The given values represent the most probable value of Landau fits.

Sensor	Epi thickness	Seed pixel		3x3 Cluster	
		ADC	S/N	ADC	S/N
0	14 μm	47.2	12.5	131.0	11.2
1		46.2	12.2	129.0	10.9
2		47.3	12.8	130.3	11.3
3	20 μm	47.5	10.9	151.4	11.0
4		46.3	12.6	147.6	13.2

Table 2: Mean values of the residual distributions for tracks fitted after the alignment.

Sensor	Mean X [μm]	Mean Y [μm]
0	-0.003 $\pm$ 0.002	-0.023 $\pm$ 0.002
1	-0.012 $\pm$ 0.004	0.036 $\pm$ 0.005
2	0.032 $\pm$ 0.004	0.005 $\pm$ 0.005
3	-0.020 $\pm$ 0.004	-0.005 $\pm$ 0.005
4	0.001 $\pm$ 0.002	-0.002 $\pm$ 0.002

The signal-to-noise ratios in the test beam 2007 was still worse than the expected performance (see Section 2.1) from laboratory tests and test beams performed by IRES Strasbourg. But, during the data taking the telescope was operated using only moderate cooling keeping the sensors at a constant temperature between 20 and 22 degrees Celsius, which is higher than in the lab tests. In addition, the new readout electronics was adding some increased noise as well. Both issues have been addressed and fixed for the tests in 2008. Preliminary results show now nominal performance, but the detailed analysis is still ongoing.

In a second step, the telescope needs to be aligned to be able to perform a track-fitting afterwards. Within the mechanical setup precision, the sensors are typically shifted by a few hundred μm in the directions perpendicular to the beam and rotated a few mrad around the beam direction, and correction factors for these shifts and rotations must be implemented in the tracking software. Table 2 shows an example of the alignment procedure for the DESY test beam at 3 GeV. The setup was using only 5 sensor planes with only about 2.5 cm of distance in between them. Tracks were fitted using the constants provided by the alignment procedure. The mean values of Gaussian functions fitted to the observed residuals in the individual planes are shown. For a perfectly aligned telescope these mean values should vanish. The results demonstrate that the alignment of the telescope is possible with very high precision around 0,05 μm, which is

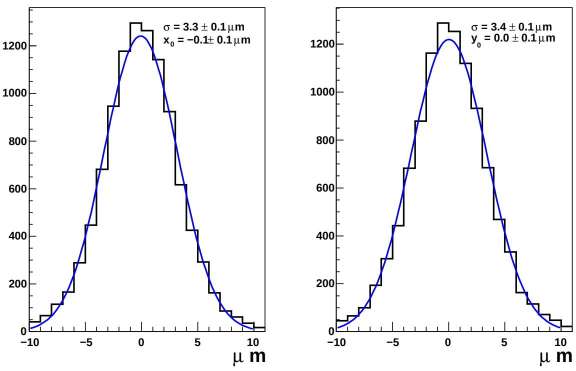

Figure 6: Residuals in the middle telescope sensor in the X (left) and Y (right) directions. This sensor was excluded from the track fit and hence acts as DUT.

more than sufficient for the intended pointing resolutions of 1-3 μm.
For track fitting, two different approaches can be followed: If multiple scattering plays no major role, a simple straight line fit can be applied. This is the case for the data recorded using a beam of 180 GeV hadrons in September 2007 at CERN. The setup of the sensors at CERN was different than at DESY: Here the sensors were mounted in two separate boxes with a gap of 34 cm for a DUT in the middle. The first box contained 3 sensors while only 2 sensors were located in the second box. Within the boxes, the sensors were mounted in a distance of 10 cm.
For the tracks, the X an Y coordinates were fitted separately. The resulting track candidates were required to fulfil a cut on $\chi^2 < 20$ in both directions. More than one track candidate per event was allowed. Figure 6 shows the residuals of the tracks in the middle out of 5 sensor planes. Here the middle telescope sensor acts as DUT while the other planes are used to predict the track positions in the DUT. The observed width is consistent with the expectation for the given telescope geometry assuming a position resolution of 3.0 μm for the DUT as well as for the other sensors used to fit tracks. Also measurements at DESY using 3 and 6 GeV electrons based on an extrapolation to infinite energy are in agreement with this sensor resolution.
To take into account multiple scattering, an analytical fit method, described in [10] has been applied and the results are shown in Figure 7. The widths of the residual distributions measured in the 5 telescope sensors are shown. The plane under study was always excluded from the track fit. Results for beams of 3 and 6 GeV electrons are in agreement with the expectation and with a simulation based on Geant4. In both cases a position resolution of the sensors of 3.0 μm was assumed. This demonstrates that a good telescope performance can be achieved even at beam energies of a few GeV.
During the summer 2008 the full demonstrator consisting of 6 sensors running in zero suppressed mode was operated at CERN. The analysis of the data from these measurements is ongoing.

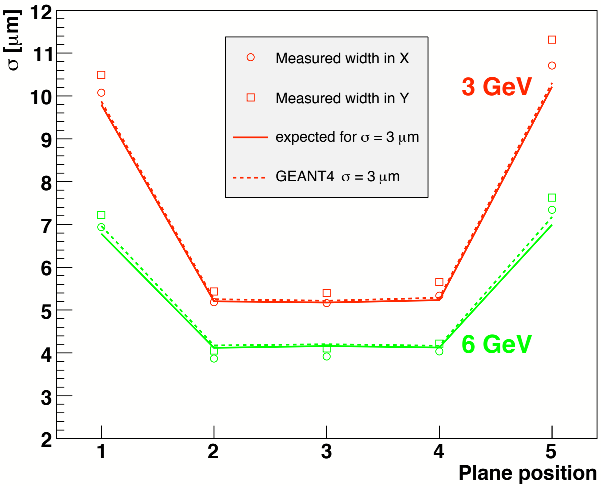

Figure 7: Residual widths in different telescope planes, using the analytical fit method.

3.2 User Campaigns

In addition to the performance evaluations of the demonstrator, several user groups have been exploiting the telescope already in 2007 (see Table 3) as well as in 2008.
Most of the users have been groups from alternative sensor technologies for the ILC like DEPFET and ISIS, but also calorimeter groups were actively using the demonstrator telescope for e.g. the study of edge and inter-pixel effects in the case of the CALICE dHCAL group. The user groups are still analysing their results.

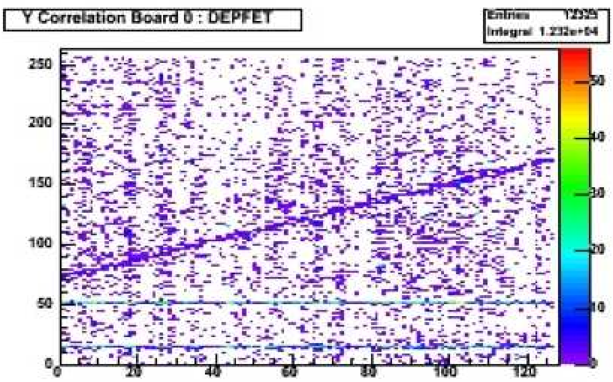

Figure 8: Correlation plot between a DEPFET sensor as device under test and a sensor plane of the demonstrator telescope. The clearly visible diagonal line shows, that the sensors are well aligned and that the events are correlated.

As one of the first users, the DEPFET group managed a full integration of their DAQ chain into the EUDAQ framework and the EUTelescope analysis chain, thus greatly simplifying event correlation and data analysis. Figure 8 shows a correlation plot between their sensor and the demonstrator telescope from within the EUDAQ monitoring

Table 3: User Campaigns and their scope in 2007 and 2008.

Date	Beam	User Scope
Sep 2007	CERN SPS 180 GeV hadrons	DEPFET Sensor studies
Dec 2007	DESY 6 GeV e^-	BeamCal Charge collection of diamond sensors
May 2008	CERN SPS	SiLC Evaluate best strip geometry
Jul 2008	CERN PS	CALICE Edge and interpixel effects of dHCAL
Jul 2008	CERN PS	DEPFET Full integration into EUDAQ
Aug 2008	CERN SPS	MimoRoma Sensor studies
Aug 2008	CERN SPS	DEPFET Sensor studies
Aug 2008	CERN SPS	ISIS Sensor studies

program.
All other groups were integrating their devices via the simplified trigger/busy scheme as explained in Section 2.4, but in all cases, the data could be efficiently correlated offline. Preliminary results from the user groups are available [?] and the final analysis is ongoing.

4 Toward the Final Telescope

4.1 Requirements

The final telescope will provide:

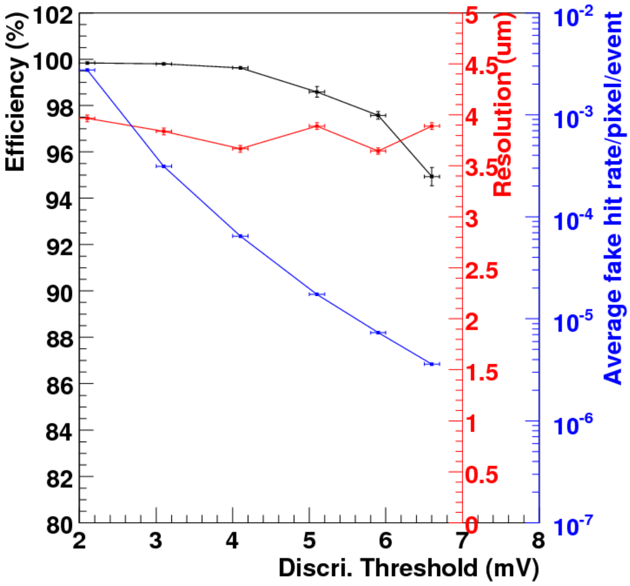

Figure 9: Typical performance of the Mimosa-22. Efficiency, resolution and average fake hit rate are shown as a function of the discriminator threshold.

- An increased sensor surface of at least 20x10 mm.
- A fully digital readout of the sensor chips.
- On-sensor correlated double sampling (CDS) and data sparsification.
- Frame rates of more than 1 kHz.
- Improved mechanics and cooling.

4.2 Intermediate sensors Mimosa-22 and SUZE-01

For the development of a sensor with a fully digital readout and on-sensor data sparsification, intermediate test sensors have been produced and validated (for more details, see [9] in these proceedings).
The concept of a column parallel architecture with discriminator outputs has been tested with the Mimosa-22 for slightly varying pixel architectures. The Mimosa-22 sensor has 136x576 pixels, a pixel pitch of 18.4 μm. 128 columns are equipped with end-column discriminators, 8 columns remain analog for debugging. A readout speed of up to 10^4 frames/second is combined with low noise values of 10-13 electrons at room temperature, resulting in a typical signal over noise ratio of about 17-22, a detection efficiency above 99.5% and a fake rate of $O(10^{-4}-10^{-5})$, comparable to the performance of the MimoTEL sensors (see Figure 9).
A data sparsification circuit has been validated with the SUZE-01. It integrates a priority look-ahead algorithm, sequencing, state selection, memories and serial transmission and has been successfully tested at the nominal speed of 10^4.

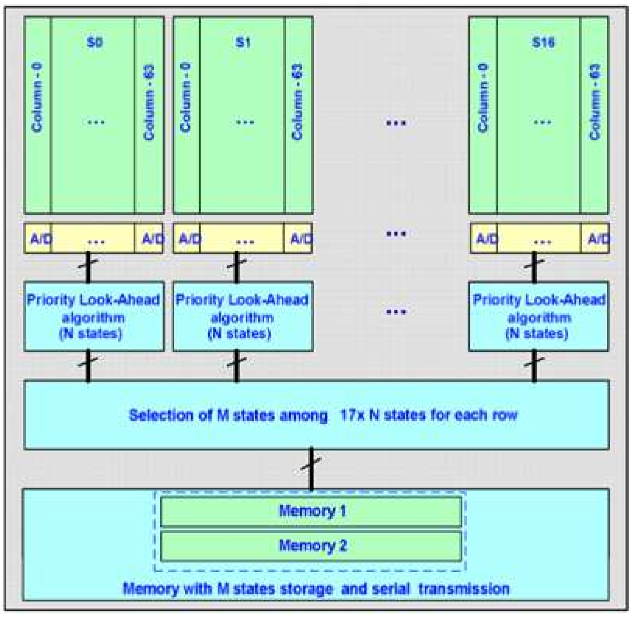

Figure 10: Block diagram of the TC/Mimosa-26.

4.3 The Final Sensor - TC/Mimosa-26

The design for the final sensor TC/Mimosa-26 is currently ongoing and will be submitted to the foundry before the end of this year. The final sensor will combine the features of Mimosa-22 and SUZE-01 and increase at the same time the active surface and number of columns by nearly a factor ten.
It will have a total of 1152x576 pixels on an active surface of 21.2x10.6 mm^2. A single point resolution of about 3.5 μm is expected, resulting in an effective pointing resolution of about 2 μm on the surface of the DUT. The frame rate will be in the order of 10^4 frames per second, resulting in data throughput of up to 80 MBit per second for one sensor.

4.4 Modifications of the DAQ

The high frame rate together with the high data throughput require also some changes on the DAQ system of the demonstrator telescope. The EUDRB is currently modified for the new sensor chip. The new version will be available beginning of 2009. In parallel, the EUDAQ is modified to prepare for the increased data speed and throughput. First tests of the full system chain (TC/Mimosa-26 → EUDRB → EUDAQ) are expected in the first quarter of 2009.

5 Conclusions and Outlook

The demonstrator telescope is running successfully during several test beam measurements since middle of 2007. Modularity was one of the most important design aspects for the DAQ hardware and software as well as for the online analysis package. The analysis of test beam data shows that the performance of the demonstrator fulfils the expectations. An increased active area, zero suppression on the sensors and improved readout speed will be offered by the final telescope, which will be available 2009. Interested groups are welcome to contact the EUDET consortium for the exploitation of the device.

Acknowledgement

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