The EUDET Pixel Telescope Data Acquisition System

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Abstract

A high resolution ($\sigma < 3\mu m$) beam telescope based on monolithic active pixel sensors (MAPS) has been built within the EUDET consortium, a coordinated detector R&D programme for a future international linear collider. A flexible data acquisition system has been developed for the telescope based on dedicated VME-readout boards for the MAPS sensors, a custom-made trigger logic unit and a platform-independent, lightweight DAQ framework. Since the first installation of a demonstrator telescope in 2007, the DAQ system has been continuously improved and adapted to new sensor types. A detailed description of the pixel telescope data acquisition system and its performance will be described in this work. The recent upgrade of the DAQ to the final sensor chip including digital readout and on-sensor data sparsification will be shown as well.

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1 Introduction

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 $\sim$1 kHz.

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 2010.

2 Overview of the EUDET Pixel Telescope

The EUDET Pixel Telescope has the following components:

- Precisely worked mechanics to position the sensor boards in the particle beam.

- Pixel sensors with a single point resolution of 2 - 3 μm and a minimum of material (see subsection 2.1).

- 3 sensors, each are usually placed in light-tight boxes before and after the DUT to form a 2-arm telescope.

- DUTs can be placed on a X-Y-Φ stage for precise positioning and scanning of the device.

- A DAQ system including hardware, trigger, and software:
  - The readout boards (EUDRB) adapted to the pixel sensors in a VME crate.
  - A VME CPU (MVME6100) to control the EUDRBs
  - A Trigger Logic Unit (TLU), controlled by a TLU-PC, to distribute the Trigger to the telescope and the DUTs
  - The DAQ Computer running the EUDAQ software framework.

- An analysis software for reconstruction, alignment and tracking.

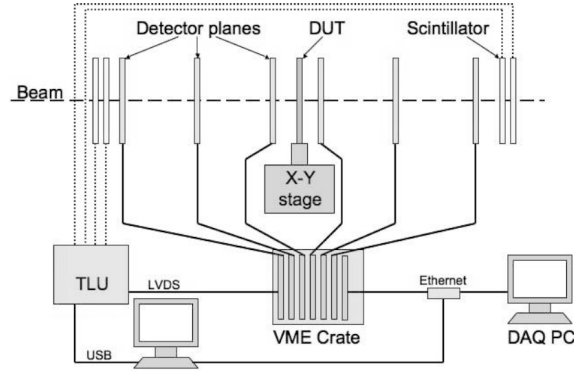In Figure 1 all main items for such a pixel telescope are shown.

Figure 1: Schematic overview of the components of the EUDET pixel telescope.

2.1 Reference Plane Sensors - MimoTel

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,

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

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 [5].
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 ∼1 μm.
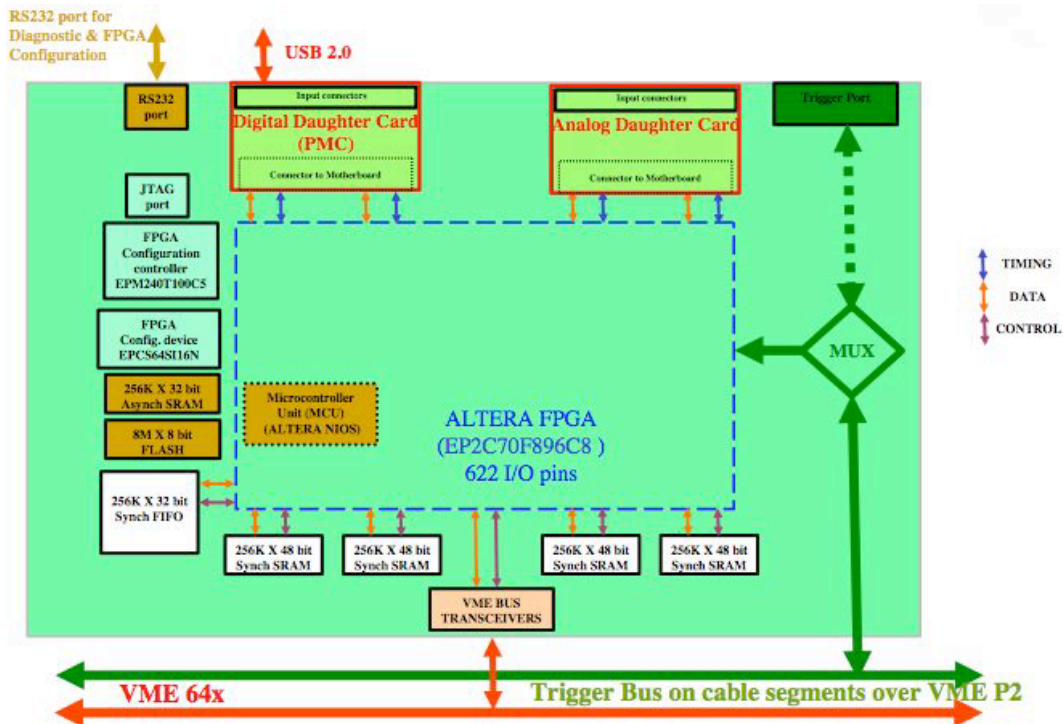
Figure 3: Schematic block diagrom of the EUDRB.

3 The Data Acquisition System

The data acquisition system for the EUDET beam telescope is a combination of dedicated hardware (Figure 1) and software with the following sketched data flow: The pixel sensors are read out by custom made data reduction boards (EUDET Data Reduction Board - EUDRB), sent via VME64x block transfer to a VME CPU (PowerPC MVME6100) and from there via Gigabit Ethernet to the central DAQ computer. This DAQ computer combines the telescope events with the information from the custom made Trigger Logic Unit (TLU), which is controlled by its own PC. The whole system is controlled by the Data Acquisition software (EUDAQ). The system allows flexible integration of multiple Devices under Test (DUTs). Offline analysis of the data is performed within the ILC software framework on the GRID using a dedicated EUTelescope package. The details to the different components are given below.

3.1 The Data Reduction Board

The EUDET Data Reduction board EUDRB [6] was developed at INFN-Ferrara in collaboration with University of Insubria-Como and INFN-Roma 3 to read out Monolithic Active Pixel Sensors (MAPS). The motherboard (EUDRB_MoBo) is a VME64x slave in 6U Eurocard format. The motherboard supports one "analog" ("EUDRB_DCA") and one "digital" ("EUDRB_DCD") daughter cards with PCI Mezzanine Card (PMC)

format. The EUDRB_DCD provides detector timing signals and it is also provides the EUDRB with a USB2.0 port for diagnostic and stand-alone data acquisition. The EUDRB-DCA has 4 single-ended/differential analog inputs and it is based on the design developed by IPHC-Strasbourg and the SUCIMA collaboration [11, 13]. The EUDRB has been so far employed with the IPHC's MIMOSA-5, MIMOSTAR 2 and MIMOTel devices (in this last case a level adapter card is necessary).

A schematic diagram of the EUDRB is shown in Figure 3. The EUDRB features four banks of 256k x 48bit SRAM memories providing storage for up to three full frames for a 1M-pixel sensor like the MIMOSA-5. On this collected data the EUDRB performs Correlated Double Sampling (CDS), pedestal subtraction and threshold comparison to reduce the data size for the events selected by the experimental trigger. The EUDRB may however provide the full frame information when the "raw" operating mode is selected. Furthermore it features a 256k x 32bit FIFO memory to provide temporary storage for data selected by a trigger and waiting to be read out. Both, a VME and a USB2.0 interface are implemented; the EUDRB may be used for reading out MAPS both in stand-alone mode on a bench-top and in a standard VME-based data acquisition system.

The VME interface of the EUDRB supports block read modes MBLT and 2eSST, the latest achieving an in-burst transfer rate of 100MB/s. The trigger input port on the front panel of the EUDRB was designed to interface it to the EUDET Trigger Logic Unit (TLU) and a trigger bus is also implemented to distribute/receive trigger information over the free lines of the VME-J2 connectors by means of a private bus on flat cable. The operation of the boards is controlled by an ALTERA Cyclone II Field Programmable Gate Array (FPGA) device in which a NIOS-II microcontroller is also implemented to do initialization, housekeeping and diagnostic.

3.2 Trigger Logic Unit

A simple easy to use trigger system is desirable for a user telescope, given that at beam-tests rapid installation of the device under test is often needed. Triggering on beam particles has traditionally been done using modules housed in NIM crates. However, NIM crates are bulky and heavy. Moreover they are either expensive if purchased new or often in poor repair if drawn from a "loan pool". In addition it is not straightforward to expand a NIM trigger system to provide trigger time-stamping, allowing self-triggered or triggerless operation of the device under test (DUT). Modern field programmable logic allows construction of a low-cost, compact and flexible trigger unit which addresses these issues.

The TLU [7] is able to provide a "classic" beam-test trigger system. Incoming beam triggers are combined in a user selectable combination and passed to one or more DUT. The TLU also keeps a record of the arrival time of each trigger. Hence it can operate as time-to-digital converter for triggerless or self-triggered DUT. Both modes are active simultaneously, allowing triggered and triggerless/self-triggered DUT to be mixed in the same beam-test.
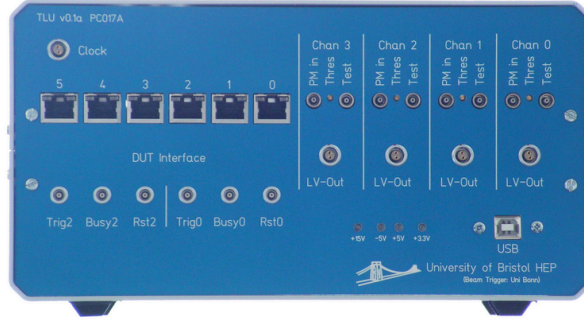
Figure 4: Front Panel of the TLU

Four 50Ω terminated coaxial connectors accept NIM,TTL or photo-multiplier level pulses and receive a trigger for each particle passing through the test-beam. These four inputs are combined to form a beam-trigger. The arrival of a beam-trigger will cause a trigger to be output to active DUTs, unless one or more have indicated that they are busy. Interface to the DUT is via RJ45 connectors each carrying four LVDS signals. The signals from the TLU to the DUT are *trigger* and *reset*, the signals from the DUT to the TLU are *busy* and *DUT-clock*. There are six DUT connectors.

The FPGA is configured via the USB interface. Memory-mapped communication is used for setup and control. Then, block transfer is used to transfer time-stamps from the TLU to the host computer.

A photograph of the TLU front panel showing the various interfaces is shown in figure 4.

There are three handshake modes available for communication between the TLU and the DUT. The modes can be mixed, with different DUT using different handshake modes. The handshake modes are:

- **No Handshake.** The TLU asserts the *trigger* line for a fixed length of time. The *busy* line from the DUT is not monitored. In this mode the TLU acts like a simple discriminator and coincidence/veto unit.

- **Trigger/Busy Handshake.** The TLU asserts the *trigger* line connected to every DUT in the system. The TLU waits for each DUT to assert its *busy* line. When a DUT does this, the TLU de-asserts the corresponding *trigger* line and waits for the DUT to de-assert its *busy* line. The TLU does not issue any further triggers until all the DUT drop their *busy* lines. This mode is illustrated in figure 5.

- **Trigger/Busy/Trigger-Data Handshake.** This mode is similar to the Trigger/Busy handshake, but trigger information is transferred from the TLU to the DUT. When the TLU de-asserts the *trigger* line in response to the DUT asserting its *busy* line, the DUT toggles its em DUT-clock line and the TLU will clock out trigger information on the *trigger* line. Normally the trigger information is the
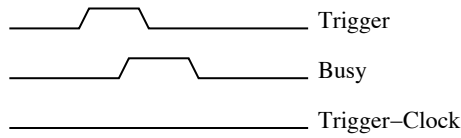
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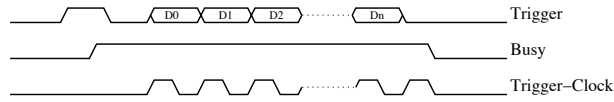Figure 5: Simple Handshake Mode
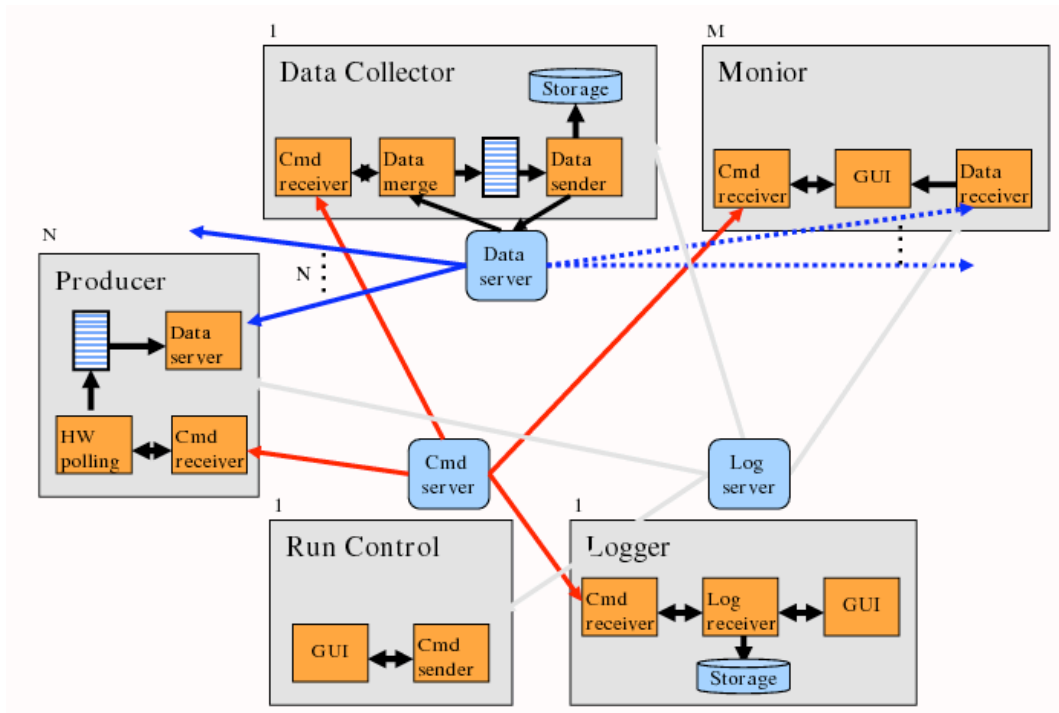

Figure 6: Trigger-Data Handshake Mode

Figure 7: Interaction between the different processes of the EUDAQ software framework.

bottom sixteen bits of the trigger counter. After the DUT is ready for new triggers and has clocked out the trigger information, it de-asserts the *busy* line. This mode is illustrated in figure 6.

3.3 DAQ Sofware - EUDAQ

The custom DAQ software named EUDAQ has been implemented in C++ [8]. Several producer tasks, that can run on different machines, communicate with a global run control using sockets. 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. Figure 7 shows the command and data flow between the different processes.

EUDAQ has been used successfully since 2007, and gradually improved performance from the initial commissioning phase to current testbeams. The demonstrator telescope is currently operated at readout speeds of about 200 Hz.

EUDAQ is multithreaded and platform independent. It runs on MacOS, Linux and Windows (with or without cygwin) and is available at hepforge [18].

3.4 User DAQ 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 offline by inter process communication. In this scenario the synchronisation and the configuration during the start-up might be difficult. The scenario has been used by some users, but is not recommended and error-prone.

- **Integration at trigger level:** This default scenario was chosen by previous 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 read by the DUT.

- **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 highest flexibility and the best integration and is followed by more and more users in current test-beams.
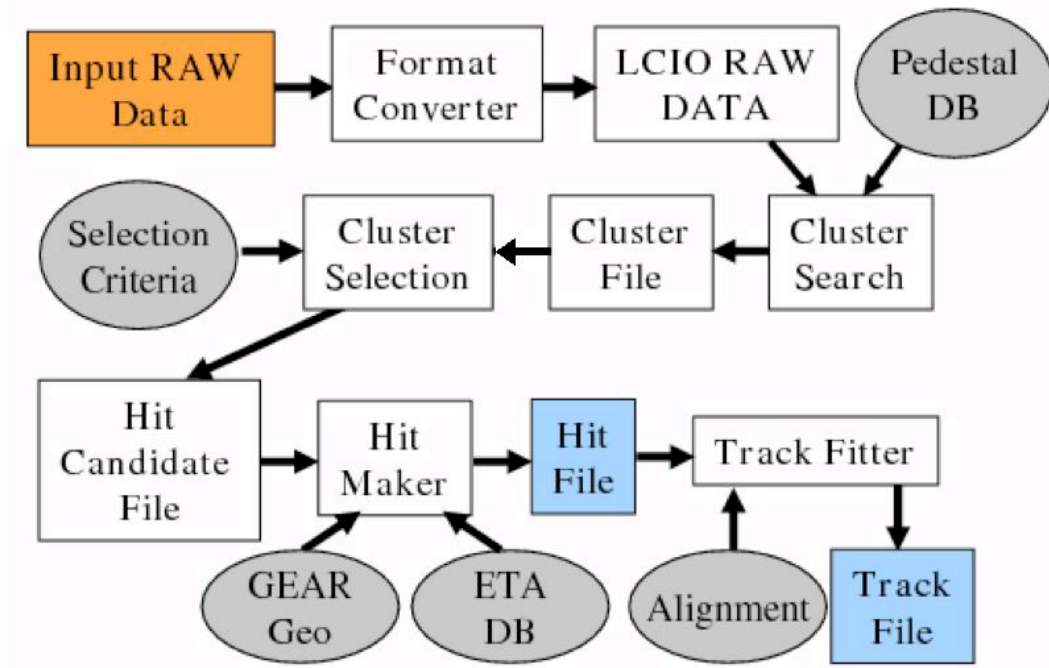
Figure 8: The overall analysis scheme.

4 The offline analysis

The main goal of the offline analysis software is to properly reconstruct the trajectory of the particles crossing the telescope reference planes and to make available to the DUT user the expected impact position on the sensor under study. The EUDET JRA1 group merged all the expertise available among the partners concerning pixel detector analysis into a completely rewritten C++ software package called EUTelescope [9]. This is a collection of Marlin [10] processors each of them responsible of a specific analysis step using LCIO as a persistent data model. The overall analysis scheme is shown in Fig. 8. Thanks to the extreme modularity of the execution framework, it is possible to execute all the analysis steps, from the native DAQ data format conversion to the track recostruction and fitting in one single execution or to stop after every single step and verify the goodness of the procedure. Here below a brief summary of the most important analysis steps.

- **From the DAQ to space points:** The very first step of the offline analysis procedure is to convert the input data written in the native DAQ format in the LCIO one using the available data model for both RAW and ZS data. This conversion step has been designed in order to be executed in a fully automatic way without any input from the user, and the converter itself is identifying the type of data in the input file and the detector type. Once the conversion is done, the pedestal and noise values are calculated on a detector by detector basis and consequently

groups of neighboring pixels are labeled as cluster using signal to noise criteria. All these analysis steps are executed detector by detector and the same procedure can also be used in laboratory experiments with radioactive sources for detector characterization and calibration. In a later stage, the center of each cluster, eventually corrected with the η function, is converted from the detector frame of reference to a space point in the global telescope frame of reference.

- **Tracker alignment:** The alignment of a tracking system is a crucial point that can heavily affect the ultimate achievable spatial resolution. For this purpose, the Millepede 2 [12] software has been fully embedded into the analysis chain within a specific alignment processor. The same processor can also be used to align the DUT with respect to the telescope reference planes.

- **Track reconstruction and DUT analysis:** Once the hit positions have been corrected with the alignment constants, it is possible to find the best fit of the particle trajectory and estimate the impact position on the DUT surface. Two different tracking processors have been implemented and used so far: a simple straight line fitter and another based on the so-called analytical approach in which the multiple scattering is also taken into account [14]. The last step is the DUT analysis and it is intentionally only marginally covered since every user is implemented his own dedicated module.

For low energy running, track displacement due to scattering of beam particles in telescope sensors, DUT or box windows, can be of the order of micrometers, comparable with the sensor position resolution. Therefore, it is crucial to take multiple scattering into account in the track finding algorithm. Following the analytical approach described in [14], dedicated track fitting method was developed and implemented in the Marlin processor called **EUTelTestFitter**. With few simplifying assumptions, which are well justified for thin sensor layers, the problem of finding track position in each telescope plane (given by the minimum of χ^2 function) can be reduced to solving of a matrix equation.

The fitting algorithm is very fast, efficient and flexible. Not only complete tracks, i.e. track with hits in all sensor planes can be searched for, but also tracks with missing hits due to sensor inefficiency. Fit procedure uses the geometry information taken from GEAR. However, additional corrections to the detector description (alignment corrections, removing passive layers from the fit) can be applied with dedicated steering parameters. Additional constraint coming from the beam direction can also be taken into account. The implemented track searching algorithm turned out to be very efficient. With high intensity hadron beam at CERN up to 100 tracks were found per event.

5 Toward the final readout system

Currently, the 'final' telescope is being built up. The main change will be the introduction of a bigger and more performant sensor chip, the TC/Mimosa-26.
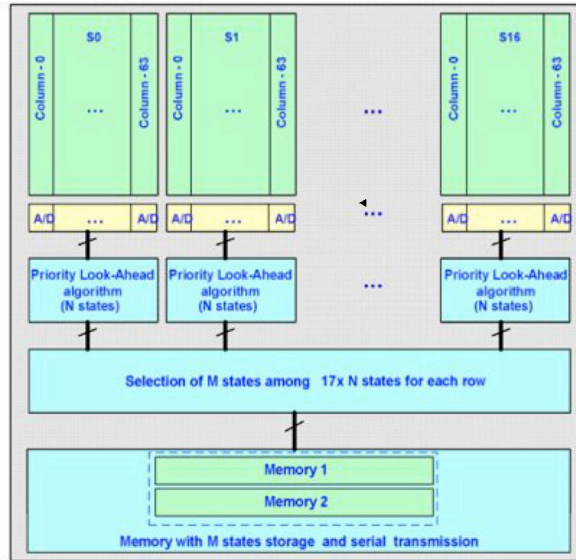
Figure 9: Block diagram of the TC/Mimosa-26.

The TC/Mimosa-26 has a total of 1152x576 pixels on an active surface of 21.2x10.6 mm^2 (an increase by a around a factor 4 compared to the MimoTel). 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.

The new TC/Mimosa-26 needs to be implemented in the current DAQ system. For the EUDRBs, a new version of the firmware is being developed which allows the board to read this new sensor with on-chip Zero Suppression and digital-only output. Only minor changes are needed to the EUDAQ framework.

The upgraded telescope will be fully commissioned in summer 2009 and exploited in 2010.

6 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 combination of the custom-made readout boards (EUDRB) together with the compact and flexible trigger logic unit has worked reliably within the newly designed and lightweight EUDAQ software framework. 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 commissioned in 2009. Interested groups are welcome to contact the EUDET consortium for the exploitation of the device.

Acknowledgement

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