The EUDET High Resolution Beam Telescope - The Final Digital Readout

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***Abstract*—A high resolution (σ<3 μm) beam telescope based on monolithic active pixel sensors (MAPS) has been built within the EUDET collaboration. EUDET is a coordinated detector R&D programme for a future linear collider providing test beam infrastructure to detector R&D groups. The telescope consists of six sensor planes with a pixel pitch of either 10 or 30 μm for the demonstrator, or 18.4 μm for the final telescope. These are located on two arms, between which a device-under-test may be positioned. A general purpose cooling and positioning infrastructure is available, along with a custom-made trigger logic unit, a flexible data acquisition system based on dedicated VME readout boards, a platform-independent, lightweight DAQ framework, and a data analysis tool based on the standard ILC software framework.**

Since the first installation of a demonstrator telescope in 2007, the DAQ system has been continuously improved and adapted to new sensor types, and has been used by a total of more than ten groups over the summers of 2008 and 2009 as a reference system for tests at DESY and the high energy hadron test beam facility at CERN. In 2008 the sensors were upgraded to the high-resolution Mimosa18 chips, providing the user with the option of enhanced resolution, at the expense of readout speed. In parallel with the 2009 test beam campaign, the final Mimosa26 sensors were installed in the demonstrator telescope as a DUT, and the readout system was adapted to the new sensors. Soon afterwards the six planes of the telescope were replaced with Mimosa26 sensors and the final telescope was commissioned.

After an overview of the pixel telescope, its data acquisition system and its performance, the commissioning of the final telescope will be presented. The main feature is the Mimosa26 sensor chip that includes on-sensor data sparsification and digital readout, allowing greatly enhanced readout speed, while maintaining good resolution.

***Index Terms*—Monolithic pixel detectors, MAPS, Telescope, Test beam, Linear Collider, ILC.**

I. INTRODUCTION

THE next great international project in High Energy Physics will be a 500 GeV electron-positron linear collider. In order to achieve that goal, an intense international planning effort with a number of R&D projects is underway. EUDET is one project within that context with the aim to improve the infrastructure for detector R&D for this future international linear collider. Within the EUDET project, the Joint Research Activity 1 (JRA1) has the task of developing test beam infrastructures, in particular the commissioning of a high resolution pixel telescope and the characterisation of a large bore 1-Tesla magnet (not covered in this document). EUDET is partially funded by the European union as a so-called "Integrated Infrastructure Initiative" within its 6^{th} Framework Programme for Research and Technological Development.

II. DESIGN GOALS

The beam telescope is designed to be used in a wide range of R&D applications with quite different devices-under-test (DUTs), and in varying beam conditions, from the low energy (1–6 GeV) electron beam at DESYII, to the high energy (>100 GeV) hadron beam at the CERN SPS. In order to be used in the widest range of conditions, the pixel telescope must have a good hit position resolution (σ<3 μm), a reasonably fast readout rate (in the kHz range), and a very limited material budget to allow an effective operation even in the presence of high multiple scattering. In addition, the overall telescope system should be small and flexible enough to be easily portable to different beam lines.

In order to quickly provide an exploitable infrastructure, the construction was planned in two stages. In the first stage (demonstrator telescope) a well established CMOS pixel technology was used to produce a telescope that did not yet reach the full requirements (in particular, the readout speed), but allowed a system that could already be used by other groups, and provide a lot of useful experience for the construction of the final system. Testing of the final sensors took place in parallel to the 2009 test beam campaign, and the final telescope was commissioned soon after.

III. MECHANICAL DESIGN

The telescope is divided into two arms (see Fig 1), each of three planes. The planes are installed on jigs positioned on a track system, allowing the positioning of the planes to be adjusted to suit the user. The lower supporting frame is connected to a cooling system [1], in order to keep the temperature of the sensors below 20 °C to minimise noise. The position of the two arms can be adjusted depending on the size of the DUT, allowing the inner planes to be placed as close as possible to the DUT, but also allowing space for large devices such as TPC prototypes. In the space between the arms there is an optional X-Y table, to enable the positioning of the DUT to be adjusted. For the final telescope, modifications have been made to improve the cooling, and to facilitate alignment of the telescope planes with the DUT.

IV. SENSORS

The sensors for the telescope have to provide a single point resolution of 2–3 μm, a reasonable lateral coverage of the DUT and a fast enough readout to reach a telescope frame rate of 1 kHz, all with a minimal of material. It was decided to use Monolithic Active Pixel Sensors (MAPS), in particular the Mimosa series of sensors developed at IPHC Strasbourg.

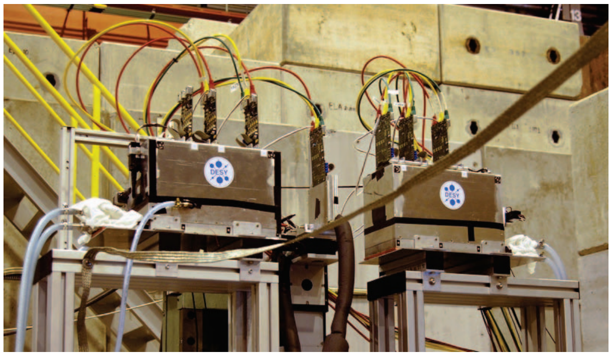

Fig. 1. The telescope installed at the CERN SPS. A single sensor is installed as a DUT, in between the boxes housing the two arms.

The MimoTel prototype was chosen for the first demonstrator telescope, providing an active area of 7.7×7.7 mm^2, with a pixel pitch of 30×30 μm^2. In 2008 the telescope was adapted to the Mimosa18 sensor, which provides an active area of 5×5 mm^2, with a pixel pitch of 10 μm [2], allowing an enhanced resolution at the expense of a slower readout rate. While these two chips show a good signal-to-noise ratio and high point precisions, they have a relatively simple architecture, without integrated data reduction, and therefore do not meet the readout speed requirements of the final telescope.

The final telescope uses the Mimosa26 chip, containing on-sensor correlated double sampling (CDS), integrated zero suppression and fully digital readout. It is fabricated in a standard CMOS 0.35 μm OPTO process, and is a combination of the Mimosa22 and the SuZe01 chips, both developed in the framework of the EUDET telescope development. The sensor contains 1152 columns of 576 pixels with a pitch of 18.4 μm [3], resulting in an active area of 21×10.6 mm^2 (see figure 2).

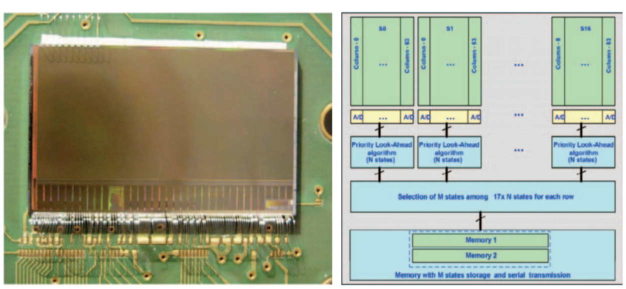

Fig. 2. A mounted Mimosa26 sensor (left), and a schematic showing the architecture of the on-chip logic (right).

The chip uses a column-parallel readout architecure in a rolling shutter mode. Pixels are read out at 80 MHz, resulting in a 112 μs integration time. Each column contains a discriminator which also performs offset compensation and correlated double sampling (CDS). Then there is a zero-suppression stage that uses a priority lookahead algorithm to perform data sparsification and write the resulting data to a memory buffer. Data volumes are compressed by a factor of 10–1000 times, depending on occupancy [4].

V. Readout System

A schematic layout of the DAQ system is shown in figure 3. The sensor is mounted on the proximity board, a PCB which includes digital and analogue signal buffering. This board is controlled by the auxiliary board which provides digital signals to drive the chip and, in the case of the demonstrator, to acquire analogue outputs.

Sensors are read out by the EUDET Data Reduction Boards (EUDRB), VME cards that read the data from the sensors. Data is then processed by an on-board FPGA and stored in a buffer before being sent over the VME64x backplane to a Motorola MVME6100 VME computer [5]. Here the data from the six planes are combined and sent over a Gigabit Ethernet connection to the central DAQ.

For the final telescope, the firmware for these boards has been largely rewritten to handle the entirely digital sensor chips and to provide additional features, such as buffering of multiple events to allow the readout of subsequent events to continue while the previous events are still being transferred via VME. It was found that the speed of the VME was a limiting factor in the readout speed, so in order to reach the design goal of a 1 kHz readout rate, the EUDRB boards were split into two VME crates, one for each arm of the telescope. In this configuration, readout rates of 990 Hz were measured with beam.

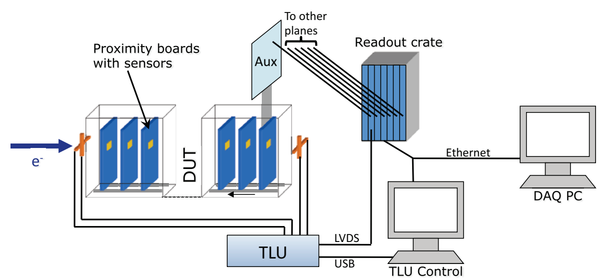

Fig. 3. Schematic of the telescope DAQ system. In the final telescope the readout boards are split between two VME crates.

VI. Trigger System

A custom Trigger Logic Unit (TLU) has been constructed. It has four inputs, which may be used as scintillator inputs or vetos, and generates a trigger signal as an arbitrary function of these signals. It also has an internal trigger generator that can be used for taking pedestals without beam, or for testing purposes. The trigger is then distributed to up to 6 DUTs, which must acknowledge the trigger, and may optionally clock out the value of the internal trigger counter [6].

The TLU has also undergone an upgrade for the final system, taking into account feedback from the first version. New features include extra LEMO connectors for DUTs to interface to, with both NIM and TTL levels, and several internal scalers, allowing easier measurements of trigger rates and efficiency.

VII. DAQ Software

A custom data acquisition framework was written for the telescope, in C++, using Posix for threads and sockets, the

Qt toolkit for the graphical interface, and Root for online monitoring histograms. It is designed to be of general use to other projects, and is portable to Linux, Mac OS X and Windows. It includes a graphical Run Control application, from which the user can control the other processes, Producers that talk to various pieces of hardware and produce data, and the Data Collector where these data are combined and written to file. A Log Collector receives log messages from all other processes, and stores them in a central location.

Several improvements have been made to the software for the final telescope. In addition to general speed and stability improvements, a plugin system has been developed to allow users to easily incorporate their decoding logic into the DAQ, and thus view information about their system in the online monitor, and analyse their data using the provided analysis software.

VIII. Analysis Software

The test beam infrastructure includes an analysis software package, namely EUTelescope, based on the standard ILC software packages LCIO and Marlin. This includes several Marlin processors to perform operations such as Pedestal Correction, Noise Calculation, Cluster Finding, Tracking and Alignment [7]. This software has been updated to handle the binary nature of the final sensors, in particular for the clustering algorithm.

IX. Beam Tests

During July 2009, three planes of Mimosa26 sensors were installed in the telescope as a DUT, with three EUDRB boards installed in a separate crate, allowing the readout system to be adapted to the new sensors and the monitoring/analysis software to be adapted to the new data encoding used by the sensors.

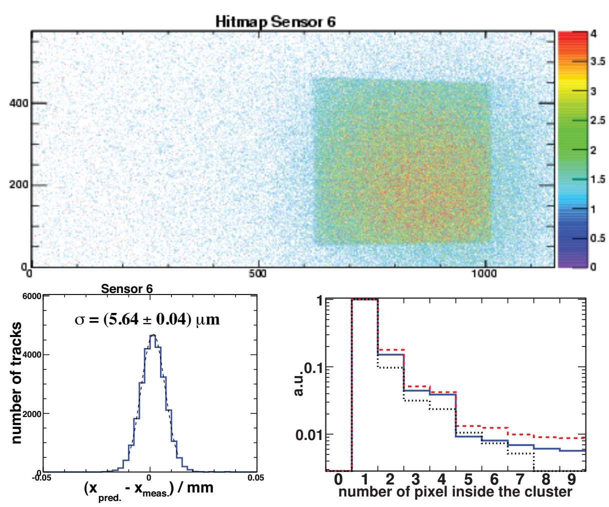

Fig. 4. Hit map for one of the sensors (top), the scintillator window is clearly visible. Residual distribution (bottom left) for one of the sensors used as a DUT. Distribution of cluster sizes in pixels (bottom right), note log scale.

Some preliminary results are shown in figure 4. In the hitmap the position of the scintillators is clearly visible, indicating that the data are being decoded properly. The measured resolution (the width of the residual distribution, equal to the sum in quadrature of the telescope resolution and the sensor resolution) is higher than expected, but this can be explained by looking at the distribution of cluster sizes. In fact, over 80% of the clusters consisted of single pixels, while a better estimate of the cluster centre leading to improved resolution would have required larger clusters. The reason for this is that the sensors were run with a too high threshold of 12 σ, leading to the complete removal of the tails of the clusters.

In September 2009 all six planes of the telescope were replaced with Mimosa26 sensors, and the EUDRB readout boards had their firmware updated to the new version. The VME readout speed was found to be a bottleneck, so the readout boards were split into two crates, one for each arm of the telescope. One of the sensors was unable to be read out correctly, so only five out of the six planes were included in the analysis. In this configuration, a readout rate of 990 Hz was measured. A total of about 2.7 million events were taken, with thresholds of 12, 10 and 8 σ.

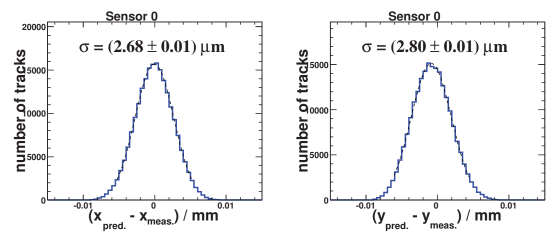

Fig. 5. Residual distribution for one plane of the final telescope, in x and in y. The sensor was not analysed in DUT mode, but was included in the tracking.

Analysis of these data are still ongoing, but some very preliminary results are shown in figure 5. The residual is shown of one plane, in x and in y. For these plots all planes were included in the track fitting, so the residuals are not directly comparable with those shown in figure 4.

X. Conclusion

The EUDET pixel telescope has been upgraded over the summer of 2009 to use the Mimosa26 sensors with on-chip zero suppression and full binary readout. This has enabled it to reach the design goal of 1 kHz readout rate. Analysis is still ongoing to verify that the resolution still meets the design goal of better than 3 μm, but this is expected to be the case. The telescope has been used by many different groups, and has been found to be a highly useful tool for the High Energy Physics community.

Acknowledgment

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